BUILDING SOIL AND FOOD SECURITY IN WHEAT PRODUCTION SYSTEMS IN TEXAS

A Dissertation

by

PEREJITEI EBIKIRIFAGHA BEKEWE

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Chair of Committee,	Haly L. Neely
Co-Chair of Committee,	Clark B. Neely
Committee Members,	Jamie L. Foster
	Katie L. Lewis
	Thomas Boutton
Head of Department,	David D. Baltensperger

May 2021

Major Subject: Agronomy

ABSTRACT

Conservation management practices such as no-till (NT) and double cropping or cover cropping are vital to food and soil security. Texas is one of the largest wheat (*Triticum aestivum* L.) producers in the U.S., and typical wheat production systems in the state use conventional tillage (CT) and summer fallow. Traditional wheat production systems can be detrimental to soil security due to soil degradation with time. The objectives of this study were to determine the effect of NT and summer double cropping systems on crop productivity including wheat crop establishment, grain yield, and herbage mass, and soil physical properties of infiltration, runoff, wet aggregate stability (WAS), and soil moisture content over time. The research was conducted for five years in three locations (Beeville, Lubbock, and Thrall, TX), which represent three distinct ecoregions in Texas (Coastal Plains, South High Plains, and Blackland Prairie respectively). Three tillage systems (NT, strip-till (ST), and CT) and five summer double cropping treatments (cowpea [*Vigna unguiculata* (L.) Walp.], sesame [*Sesamum indicum* L.], sorghum [*Sorghum bicolor* (L.) Moench], fallow, and a seven-species cover crop mixture) in an annual wheat cropping system. Tillage and summer double cropping impacts on wheat stand establishment, grain yield, and herbage mass were variable across years and locations. Tillage had inconsistent effects on cowpea pulse, sesame seed, and sorghum grain yield in different years and locations. Tillage or summer double cropping effects on infiltration rates, runoff rate were minimal. Tillage or summer double cropping (except Thrall), did not affect wet aggregate stability, however, there was an increasing trend over time across ecoregions. Soil moisture was impacted by tillage and summer double cropping during the summer with CT least at Beeville and Lubbock, while CT was greater than NT and ST at Thrall. Grain sorghum and sesame used more soil moisture than other crops; however, soil moisture recovered prior to wheat planting from fall precipitation events in most cases. Wheat-summer double cropping rotations with sesame and sorghum may improve producers' annual net return and long-term sustainability compared to cover crop and summer fallow rotations in the Coastal Plains and Blackland Prairie.

DEDICATION

I am dedicating my Ph.D. dissertation to my late mother, Fidentei Bekewe, and my late sister, Kimegbere Ebipatei Bekewe, for their unconditional love, inspiration, and sacrifices they made to ensure I have a quality education and brighter future.

ACKNOWLEDGEMENTS

I would like to thank my PhD committee, Dr. Haly L. Neely, Dr. Clark B. Neely, Dr. Jamie L. Foster, Dr. Katie L. Lewis, and Dr. Thomas Boutton, for their mentorship, support, and guidance throughout my Ph.D. Program.

I would also like to express appreciation to Dr. Terry Gentry for his great advice and laboratory space to conduct part of my research. Thanks to Dr. Ronnie Schnell, Dr. Fernando Guillen, Ryan Collett, Maureen Victoria, Nick Frisbee, Brittany Garza, Carlos Serna, Stephanie Garza, Amelia Garza, Morgan Sanders, Jacobb Pintar, Darius Ford, Shelby Harrell, Dustin Kelley, Joseph Burke, Amee Bumguardner, Walker Crane, and Dr. Ayush Joshi Gyawali for their technical support with field and laboratory activities.

Special thanks to Jones Okoro, Joseph Okoro, and my family for their undying support, motivation, and prayers throughout the course of my Ph.D. program.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a dissertation committee consisting of Dr. Haly L. Neely (advisor), Dr. Clark B. Neely (co-advisor) of the Department of Soil and Crop Sciences, and committee members Dr. Jamie L. Foster and Dr. Katie Lewis from Texas A&M AgriLife Research with graduate faculty status in Department of Soil and Crop Sciences,, and Dr. Thomas Boutton of the Department of Ecology and Conservation Biology.

Funding Sources

This material was supported by the Natural Resources Conservation Service, U.S. Department of Agriculture, under number NR183A750008G013. Additional funding sources include Texas A&M AgriLife Research Cropping Systems Improvement Grant as well as NRCS-Texas State Office.

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

1.1. Overview of The Research Problem

Productivity, sustainability, and soil health information are all vital to the development of agricultural management recommendations. In order to make decisions, producers need information about tillage, crop rotations, and water and soil management practices that improve soil health and function. Healthy soil is capable of supporting the production of food and fiber, to a level and with a quality sufficient to meet human requirements, together with continued delivery of other ecosystem services that are essential for maintenance of the quality of life for humans and the conservation of biodiversity (Doran and Zeiss, 2000; Kibblewhite et al., 2008). Organic carbon (OC) is a major driver of soil health and sustainability. Soils with greater OC tend to capture more water during rain or irrigation events, cycle nutrients more effectively, and are less prone to erosion (USDA-NRCS, 2017). Management practices, such as tillage and crop rotation, can have significant impacts on soil OC and therefore soil function (NRCS, 2017). For example, no-till systems can build soil OC through slower decomposition of crop residues. Additionally, diverse crop rotations have been shown to magnify the beneficial impacts of reduced tillage (Keeling et al., 1989). In contrast, traditional management practices, such as continuous cropping and conventional tillage, over time can lead to poor soil health, which may decrease long-term sustainability and economic viability.

Wheat (*Triticum sp.*) was the second most planted crop in Texas in 2017, with an estimated 1.9 million hectares with 68.15 million bushels produced and ranked as the ninth state in the United States for production (Neely et al., 2017; USDA-NASS, 2018). In Texas, livestock graze 40-45% of wheat and 50% of Texas' wheat is exported to foreign markets (Neely et al., 2017). The majority of wheat production systems in Texas are managed under more conventional practices of full tillage and summer fallow, which may be detrimental to soil health, long-term sustainability, and productivity objectives. Wheat is often followed by a summer fallow period, opening the opportunity to include summer-planted double crops such as grain sorghum (*Sorghum bicolor* (L.) Moench). Reduced tillage, and double cropping during the traditionally fallow period, may improve productivity and soil health in wheat cropping systems. Borchers et al. (2014) reported that only 2.1% of agricultural lands are utilized for double cropping in the Southern Great Plains of Texas. Dobberstein (2014) reported that only 8.8% of agricultural lands in Texas are used for no-till farming. This ranks Texas poorly in the U.S. in terms of adoption of no-till practices. Information on how combined effects of conservation practices (i.e. reduced tillage and increased cropping system diversity) on soil physical properties, soil OC, microbial activities, wheat productivity, and the impact of these management strategies on profitability in this region is needed.

1.1.1. Objectives

The primary purpose of these studies was to fill knowledge gaps about management decisions, such as cropping system intensity (fallow, cover crop, or double crops) and tillage intensity (no-till, strip-till, or conventional tillage), that may improve soil health and function in wheat cropping systems. Our specific objectives focused on the physical, chemical, and biological aspects of soil health as well as agricultural productivity and include:

1. Determine the impact of cropping system diversity and tillage intensity on overeall cropping systems productivity.

2. Quantify the effect of cropping system diversity and tillage intensity on soil physical properties including temporal variation in soil moisture, wet aggregate stability, and soil water infiltration.

1.2. Literature Review

1.2.1. Wheat

Wheat is one of the most sought-after agricultural products in the world and has been identified as one of the major sources of food supply and security due to its high-quality nutrition and health benefits especially in developing countries (FAO, 2011; Farvid et al., 2016; and Slavin, 2004). There are three primary wheat species that are popular among producers: *aestivum*, *durum*, and *spelta*. Wheat was the second most planted crop in Texas in 2017 with an estimated 1.9 million hectares with 68.15 million bushels produced and ranked as the ninth state in the United States for production (USDA-NASS, 2018; and Neely et al., 2017). In Texas, 40-45% of wheat acres are used for livestock grazing, while 50% of wheat produced in Texas is exported to foreign markets (Neely et al., 2017). Other alternative uses of wheat are straw, particle board, paper, hair conditioner, postage stamp adhesive, medical swabs, charcoal, biodegradable plastic, and cleaning utensils (Neely et al., 2017).

Cereals made up an estimated 49% of world food consumption (Alexandratos and Bruinsma, 2012). With the growing world population estimated to be 9 billion by the year 2050, resources such as water, land and nutrients will become scarcer and more cereal crop production will require a 45.5% increase to meet the food demand (Alexandratos and Bruinsma, 2012). Healthy agricultural lands, water, and other resources have become more limited by poor management strategies resulting in degradation of soil, salinity (especially due to irrigation), and decline in productivity (Alexandratos and Bruinsma, 2012). In Texas, much of the wheat is produced using conventional tillage and summer fallow which may be detrimental to soil health, long-term sustainability, and productivity objectives. Tillage may result in a reduction in soil OC, which decreases aggregate stability and increases soil degradation (Alvarez and Steinbach, 2009; Tebrugge and During, 1999). Researchers have indicated methods to increase crop productivity as well as maintain soil quality, such as soil amendments like plant-based biochars (Weyers and Spokas, 2014); crop residue retention (Pittelkow et al., 2014); increased plant straw additions (Kahlon et al., 2013; Tejada and Benítez, 2014); diversified crop rotations (Pittelkow et al., 2014), and conservation tillage systems, such as no-tillage (Kahlon et al., 2013). Most farmers see agricultural practices as solely for crop or livestock food production (Grünwald et al., 2000); whereas, food production depends on soil-based ecosystem functions such as nutrient cycling, maintenance of soil structure, and biotic population regulation (Grünwald et al., 2000; Kibblewhite, et al., 2008). Food availability can be improved through double cropping wheat with warm-season annuals and can increase the profitability for producers (Alexandratos and Bruinsma, 2012).

1.2.2. Double Cropping

Double cropping can be defined as planting and harvesting more than one crop from a unit of land annually. Double cropping wheat with warm-season annuals has the potential to increase the farmer's net return compared to planting only wheat annually (Alexandratos and Bruinsma, 2012). A USDA national survey given between 1999 to 2012 estimated only 2% of all cropland was farmed with double cropping (Borchers et al., 2014). Farmers' skepticism about double cropping systems was attributed to water availability or low precipitation that may affect their primary crop (Borchers et al., 2014; Unger et al., 2006). Nevertheless, studies have shown that residues or ground coverage on the soil's surface create a physical barrier resulting in less water evaporation and greater protection from erosion than fields without ground coverage (Massee and Cary, 1978; Shangning and Unger, 2001). Researchers also found that the combination of double cropping and reduced tillage intensity increased soil moisture conservation, productivity, and net returns (Dhuyvetter et al., 1996; Baumhardt et al., 1985; and Unger et al., 1984). Yearly declines in acres of farmlands have been reported (USDA-NASS, 2017); this continued decline is detrimental to world food production and cropping system intensification is needed to offset these losses. Double cropping is one potential alternative to meet increasing food demands with less farmland.

The traditional wheat production system in the U.S. is mostly practiced in dryland regions with low rainfall. Winter wheat production depends on soil moisture availability at the time of planting, hence, the fallow period is important for capturing and storing rainfall in the soil for subsequent wheat crop (Hinze and Smika, 1983; Nielsen, 2005; Nielsen et al., 2002; Nielsen et al., 1999; Stone and Schlegel, 2006). Nielsen et al. (1999) in the Great Plains reported wheat-sunflower [*Helianthus annuus* L.] rotation resulted in a decrease in wheat yield by 7.9 kg ha^{-1}. Stone and Schlegel (2006) in the Great Plains reported that in wheat-sorghum rotation, every millimeter of water added at crop emergence resulted in increased grain yields for 22.1 kg ha^{-1} for sorghum and 9.8 kg ha^{-1} for wheat. Massee and Cary (1978) reported less than 30% of precipitation was stored during the summer fallow period and suggested that the water loss may be due to the exposure of the soil surface to wind and solar energies that facilitate evaporation coupled with erosion. Blanco and Lal (2008) suggested that keeping ground coverage year-round will control erosion and increase OC, resulting in improved soil structure and greater water holding capacity.

The combination of double cropping with reduced tillage has been considered an option to increase productivity, soil coverage, and improve soil structure by the aforementioned researchers; however, identifying the proper double crop option to rotate with wheat in Texas is still a challenge. Borchers et al. (2014) identified soybean [*Glycine max* (L.) Merr.], corn [*Zea mays* L.], and grain sorghum as the most planted warm-season crops for rotation with winter wheat. In Texas, winter wheat and fall-planted spring wheat are harvested in May or June; therefore, selecting a summer crop that will be harvested prior to wheat planting in November or December is key to ensuring wheat-double crop rotation functionality. This project includes the following warm-season crops with wheat rotations: cowpea, a seven species cover crop mix, grain sorghum, and sesame [*Sesame indicum* L.].

1.2.2.1. Cowpea [*Vigna unguiculata* (L.) Walp]

Cowpea [*Vigna unguiculata* (L.) Walp] is a leguminous crop that serves as forage for livestock consumption as well as human consumption and is grown in Africa, subtropical regions of Asia, Middle East, Europe, South America, Central America, and the Southern region of the U.S. (Singh, 2014a). Cowpea species are tolerant to drought, heat, and water stresses and between 200 to 350 mm of rainfall is required (Singh, 2014a). Because cowpeas are leguminous plants, they can fix atmospheric N into bioavailable N through symbiotic relationships with *Rhizobium* bacteria that colonize root nodules. Thus, cowpeas have the capacity to incorporate 160 kg ha^{-1} of N into the soil within 60 days and may reduce the N fertilizer application for the subsequent crop (in this case, wheat) by 40 kg ha^{-1} (Singh, 2014a). The global average for cowpea grain production per hectare is estimated to be 500 kg ha^{-1}: however, with proper management, the grain yield could potentially increase to between 2000 to 3000 kg ha^{-1} (Singh, 2014a). Singh (2014a) suggested that cowpea grain yields in a wheat-cowpea rotation could reach 2000 kg ha^{-1}.

1.2.2.2. Grain Sorghum [*Sorghum bicolor* (L.) Moench]

Grain sorghum is one of the most utilized cereals in the world and is ranked third for production and hectares planted in the U.S. and fifth globally (FAO, 2016). Grain sorghum is mainly used for livestock production in the U.S.; however, worldwide it is an important crop for human consumption as well as animal feed. Grain sorghum is commonly grown across the southern U.S. (3.4 million hectares in 2015) and Texas (1.1 million hectares) is second in the U.S. in planted acres (USDA-NASS, 2016). Grain sorghum has unique characteristics that differentiate it from most grain crops, including the ability to excel in drought, wet soils, and flooded environments (Carter et al., 1989). Additionally, grain sorghum requires at least 27 to 32°C daytime temperatures in July to optimize photosynthesis (Carter et al., 1989), making it ideal for Texas climates.

1.2.2.3. Sesame [*Sesame indicum* L.]

Sesame is a crop that is highly tolerant to heat, drought, insects and pests and is produced in the arid and semi-arid regions of the south, southeastern, and southwestern U.S. because the soils in these regions are well drained (USDA-NRCS, 2014; Langham et al., 2010). Double cropping sesame with wheat has the potential to increase farmer's income due to the high demand and market prices of sesame (Langham et al., 2010; Morris, 2002). Currently, sesame imports to the U.S. exceed the export market creating opportunity for the sesame industry to grow and compete in the global marketplace (USDA-NRCS, 2014). Sesame is primarily grown for oil production, which is used for cooking oils, paints, soap production, cosmetics, insecticides, and animal protein meal, among others (Myers, 2002). Langham et al. (2010)

recommended late planting in colder regions as early freezing events will facilitate termination of the crop. Sesaco Corporation (Austin, TX), a vertically-integrated sesame specialty company, recommended wheat-sesame rotations have the potential of producing 896 kg ha^{-1} yields in San Angelo, TX (Langham et al., 2010).

1.2.3. Cover Cropping

Cover crops are grown essentially to prevent soil erosion through ground coverage (Magdoff and Van Es, 1993). In a cover crop mix, greater diversity is recommended as it promotes nutrient scavenging and cycling, and diverse root systems facilitate improvement of soil quality and soil structure which ultimately increase yields for the subsequent crop (Thorup-Kristensen, 2001; USDA-NRCS, 2012a). Cover crops have the potential to increase soil security through soil protection from wind and water erosion as the soil surface is well covered by the cover crop (Blanco-Canqui et al., 2013). In Texas, summer cover crop species must be heat and drought tolerant. A cover crop study conducted for four years at the Natural Resources Conservation Service (NRCS) Plant Materials Centers in the Southeast region of U.S. indicated that legumes such as Sunn hemp [*Crotalaria juncea* L.], 'Iron and Clay' cowpea, and lablab [*Lablab purpureus* (L.) Sweet], and the warm-season grass Japanese millet [*Echinochloa esculenta* (A. Braun) H. Scholz] resulted in greater biomass production and ground coverage than the comparison crops (NRCS-USDA, 2018).

The seven cover crop species planted as a mixture for this research project were Buckwheat ['Mancan', *Fagopyrum esculentum* Moench], Cowpea 'Iron and Clay', Guar ['Kinman', *Cyamopsis tetragonoloba* (L.) Taubert] Lablab 'Rio Verde', Pearl millet [*Pennisetum glaucum* (L.) R. Br.], Short Stature Sunflower '8H668S', and Sunn hemp. The species consist of legumes and grasses selected based on their drought tolerance, adaptability to heat stress, and greater biomass production. Mancan buckwheat is nonlegumious, C_3 photosynthetic pathway forb which is typically grown in the cool-season and has a short growing season. Benefits of Mancan buckwheat as a cover crop include helping to promote soil aggregation, and nutrient scavenging, specifically of calcium and phosphorus (Björkman, 2014). Iron and Clay cowpeas are a blend with indeterminate growth habit that produces high biomass and is considered a heat and drought tolerant forage legume (SARE, 2012). Biomass yield of Iron and Clay was approximately 3,500 and 6,400 kg ha^{-1} in Beeville and Stephenville, TX, respectively, averaged over two growing seasons (Foster et al., 2017). Guar 'Kinman', is a drought tolerant, summer annual legume that originated from Africa (Baath et al., 2018). Guar requires 90 to 120 days (shorter-duration crop) to reach maturity and can be used effectively in different crop rotations (Rao and Northup, 2009, 2013). Grain yields of 1.1 to 1.8 Mg ha^{-1} and herbage mass yields of 2.9 to 3.8 Mg ha^{-1} were reported for eight different varieties of guar grown near Las Cruces, NM (Singh, 2014b; Singla et al., 2016a; Singla et al., 2016b). Guar has been reported to improve soil through its soil-binding roots and N-fixation that are beneficial to subsequent crops (Tripp et al., 1982; Wong and Parmar, 1997). 'Rio Verde' lablab is also a leguminous crop that has potential for high biomass production, is heat and drought tolerant, and can be used as a forage legume for livestock production, human consumption, and in N scavenging (USDA-NRCS, 2012b). Biomass yield of 'Rio Verde' lablab in Beeville and Stephenville, TX, over two growing seasons was approximately 3,000 kg ha^{-1} (Foster et al., 2017). Pearl millet is a warm-season grass that produces large amounts of biomass, is resistant to drought and heat stress, and can be utilized as forage due to high nutritive values and low levels of toxicity from prussic acid (Newman et al., 2014). Sunflower '8H668S' can withstand drought and heat stress due to a large taproot system that aids deeper nutrient scavenging and infiltration into the soil profile (Meyers, 2010). Sunn hemp is a tropical legume that helps to improve soil by the addition of organic matter (OM) and N and helps to suppress root-knot nematodes (Rotar and Joy, 1983). ‘Kauffman’ sunn hemp produced almost 10,000 and over 13,000 kg ha^{-1} of biomass in Beeville and Stephenville, TX, respectively, over two growing seasons; whereas, ‘Tropic Sun’ sunn hemp only produced 8,600 and 11,000 kg ha^{-1} (Foster et al., 2017).

1.2.4. Tillage Management

No tillage has long been considered one of the most important management practices for sustainable cropping intensification to meet future global food demands (Derpsch et al., 2014) while preserving soil security by reducing soil erosion (Lal, 2001), and increasing soil health through increases in soil OC content and aggregate stability (Alvarez and Steinbach, 2009) and biological activity (Anken et al., 2004). In NT systems, residues left on the soil surface after crop harvest have been suggested to be a driving force for promoting microbial activity, improving aggregate stability, and protecting against erosion (Tebrugge and During, 1999). Less disturbed soils and the maintenance of cover from crop residues in reduced or no-till systems improves soil properties (Tebrugge and During, 1999). Soils that have undergone long-term NT were characterized by higher resistance against stress from vehicle load, higher stability of aggregates against the impact of raindrops, lower susceptibility to soil crusting and erosion, and a high abundance of vertically oriented continuous earthworm burrows resulting in increased infiltration rates and reduced soil losses (Tebrugge and During, 1999). Tebrugge and During (1999) reported that surface cover from crop residues resulted in higher aggregate stability and protected soil by avoiding surface sealing and erosion under no-till practices. Accumulation of organic matter and nutrients near the soil surface under no-till and reduced tillage were favorable consequences of not inverting the soil and by maintaining a mulch layer on the surface

(Tebrugge and During, 1999; Tebrugge et.al., 1991). This was a result of enhanced biological activities in the no-till and reduced tillage topsoils (Tebrugge and During, 1999), and increased earthworm activity in no-till was associated with a system of continuous macropores which improved water infiltration rates (Tebrugge and During, 1999).

Foley et al. (2011) suggested that high yielding, conventional agricultural systems used greater quantities of fossil fuels and had greater nutrient demand, soil degradation, and environmental pollution, specifically water pollution due to nitrate and phosphate fertilizers eroding into rivers. No-till combined with crop rotation and soil ground coverage/residue retention has been observed to reduce cost of production due to decreased energy and labor requirements, while increasing yields and profitability compared to CT agriculture system (Erenstein et al., 2012). In Texas, cotton (*Gossypium hirsutum* [L.]) and sorghum managed with NT had less annual operating expenses primarily due to decreased fuel and labor costs (Foster et al., 2018). Despite the abundance of scientific literature on the topic of NT systems, little consensus has been made as to whether yields are maintained, increased, or decreased under NT management (Brouder and Gomez-Macpherson, 2014; FAO, 2011; Giller et al., 2009). No tillage has been shown to increase yields under water-limited environments (Farooq et al., 2011; Rusinamhodzi et al., 2011). However, studies have also shown NT practices resulted in low productivity as a result of possible soil water-logging and cooler soil temperatures which can have negative impact on crop stands (Anken et al., 2004; Hay et al., 1978; Mikkola et al., 2005; Van Ouwerkerk and Perdok, 1994; Riley et al., 1994; Soane et al., 2012). Cool, wet soils can lead to soil compaction affecting root growth or lead to poor soil fertility and consequently nutrient deficiencies (Ogle et al., 2012; Van den Putte et al., 2010; Alvarez and Steinbach, 2009). Other challenges with NT system are the difficulty of adequate seed-to-soil contact at planting, and it takes time and experience for farmers' to adjust to NT equipment properly and the needed adjustments are often site specific. Lewis et al. (2018) reported greater cotton lint yield with CT compared to NT in the Texas High Plains. Other research indicates no difference between crop yield in NT or full-tillage management (Foster et al., 2018).

1.2.5. Soil Health

Soil is home to the largest organic carbon reservoir in terrestrial ecosystems, containing three times more carbon than the vegetation they support (Post et al., 1982). Agricultural practices that delay the release of carbon into the atmosphere, or build soil carbon, are needed more than ever in the 21st century to increase C sequestration thereby minimizing the impact of CO_2, which is one of the most important greenhouse gases in the atmosphere (Anwar et al., 2020). Identifying and recommending sustainable cropping systems that will result in longevity of C sequestration, improved nutrient cycling, and water capture and storage without negatively impacting yields are essential to meet agricultural sustainability and soil health goals. Understanding the dynamics of cropping systems and agricultural management practices that are productive and enhance soil health and function without compromising yield and profitability are very important in tackling challenges of soil degradation and long-term sustainability.

Soil health is a dynamic property that reflects the capacity of soil to support agricultural production and the provision of other ecosystem services (Kibblewhite et al. 2008). A healthy soil depends on four major components: 1) C transformations, 2) nutrient cycling, 3) soil physical structure stability, and 4) pests and disease control (Kibblewhite et al., 2008). The diversity and interaction of soil microorganisms in an abiotic soil environment, termed as biological processes, are key to the proper function of the four components that define soil health. One of the major knowledge gaps regarding soil health is how to manage and conserve the soil for ecosystem services and at the same time increase crop productivity. Sustainable farming systems require agricultural practices that will promote soil health and long-term productivity without compromising ecosystem services. Soil conservation practices such as crop rotation, cover crop use, and reduced tillage intensity are potential options to improve soil health and increase crop productivity.

Soil security, defined as the protection and improvement of our soil resources, is supported by management practices that build soil OC. Soil OC storage can be defined as the net effect of OC inputs to the soil and losses through decomposition (Amundson, 2001; Schlesinger, 1997). The intensive use of heavy equipment, conventional tillage, and continuous dependence of synthetic fertilizers are examples of agricultural practices that contribute to long-term decreases in productivity and increase soil degradation (Gold, 1999; Hobbs et al., 2007; Holland, 2004; Hussain et al., 1998; Lal, 1994; Raper et al., 2000). Soil management is important to all agricultural systems; however, degradation of agricultural lands due to erosion, loss of OC, contamination, compaction, and increased salinity, among other effects, are evidence of poor soil management practices (European Commission, 2002). Soil degradation can occur rapidly due to poor soil management which can lead to issues such as gully erosion (Kibblewhite et al., 2008). It can also occur slowly over time and may influence agricultural production negatively (Kibblewhite et al., 2008). Intensive tillage is an agricultural practice that may result in decreases of environmental services, such as C sequestration and nutrient cycling, which may affect farmers over time (Kibblewhite et al., 2008).

Several methodologies for assessing soil health and quality have been suggested, however, most of the methods are no longer in use (Doran et al., 1994). The Soil Management Assessment Framework Design (SMAF), Andrews et al. (2004a), and the Comprehensive

Assessment of Soil Health (CASH; Moebius-Clune et al., 2016) are more recent methods for soil quality measurements. Unlike the above two indices, the Haney Soil Health Index focuses on labile soil OC pools and biological activity that utilizes different measurements (C:N ratio, Cmin, water-extractable OC (WEOC), and water-extractable organic N (WEON)) of the active fractions of soil C and N (Haney, 2014; Haney et al., 2012). Grading soil numerically will be helpful in the evaluation of the health of a soil, which may be useful in determining management strategies that a farmer can apply to improve the soil and increase productivity (Beniston, 2015; Andrews et al., 2004b; Nakajima et al., 2016). The Soil Health Institute listed the following as soil health indicators: OC, pH, texture, penetration resistance, crop yield, water-stable aggregation, cation exchange capacity (CEC), electrical conductivity, N, P, K, C mineralization, N mineralization, erosion rating, base saturation, bulk density, available water holding capacity, micronutrients, and infiltration rate (Soil Health Institute, 2016).

1.3. References

Alexandratos, N., and J. Bruinsma. 2012. World agriculture towards 2030/2050. Land use policy 20: 375.

Alvarez, R., and H.S. Steinbach. 2009. A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crop yield in the Argentine Pampas. Soil Tillage Res. 104:1-15. doi:10.1016/j.still.2009.02.005.

Amundson, R. 2001. The carbon budget in soils. Annual Review of Earth and Planetary Sciences 29:535-562.

Andrews, S.S., D.L. Karlen, and C.A. Cambardella. 2004a. The Soil Management Assessment Framework : 1945–1962.

Andrews, S.S., D.L. Karlen, and C.A. Cambardella. 2004b. The Soil Management Assessment Framework: A Quantitative Soil Quality Evaluation Method. Soil Sci. Soc. Am. J. 68:1945–1962.

Anken, T., P. Weisskopf, U. Zihlmann, F. Hans-Rudolf, J. Jansa, K. Perhacova. 2004. Long-term tillage system effects under moist cool conditions in Switzerland. Soil Till. Res. 78:171-183. doi:10.1016/j.still.2004.02.005.

Anwar, M.N., A. Fayyaz, N.F. Sohail, M.F. Khokhar, M. Baqar, A. Yasar, K. Rascool, A. Nazir, M.U.F. Raja, M. Rehan, M. Aghbashlo, M. Tabatabaei, and A.S. Nizami. 2020. CO2 utilization: Turning greenhouse gas into fuels and valuable products. J. of Environ. Management. 260:1–14. doi:10.1016/j.jenvman.2019.110059.

Baath, G.S., B.K. Northuo, A.C. Rocateli, P.H. Gowda, and P.S. Neel. 2018. Forage Potential of Summer Annual Grain Legumes in the Southern Great Plains. Agron. J. 110:2198 – 2210. doi:10.2134/agronj2017.12.0726.

Baumhardt, R.L., R.E. Zartman, and P.W. Unger. 1985. Grain sorghum response to tillage method used during fallow and to limited irrigation. Agron. J. 77:643–646.

Beniston, J.W., R. Lal, and K.L. Mercer. 2015. Assessing and managing soil quality for urban agriculture in a degraded vacant lot soil. Land Degrad. Dev. 27:996–1006.

Björkman, S. 2014. Cover Crop Fact Sheet Series: Buckwheat. Cornell Univ.: 1–2.

Blanco-Canqui, H., J.D. Holman, A.J. Schlegel, J. Tatarko, and T.M. Shaver. 2013. Replacing fallow with cover crops in a semiarid soil: effects on soil properties. Soil Sci. Soc. Am. J. 77:1026-1034.

Blanco, H., and R. Lal. 2008. Principles of soil conservation and management. Principles of soil conservation and management. Springer, Berlin. 2008.

Borchers, A., E. Truex-Powell, S. Wallander, and C. Nickerson. 2014. Multi-cropping practices: recent trends in double cropping, EIB-125. U.S. Department of Agriculture, Economic Research Service, May 2014.

Brouder, S.M., H. Gomez-Macpherson. 2014. The impact of conservation agriculture on smallholder agricultural yields: a scoping review of the evidence. Agric. Ecosyst. Environ., 187:11-32.

Carter, P.R., D.R. Hicks, E.S. Oplinger, J.D. Doll, L.G. Bundy, R.T. Schuler, and B.J. Holmes. 1989. Alternative field crops manual, grain sorghum (Milo). Univ. of Wis., Coop. Ext. https://hort.purdue.edu/newcrop/afcm/sorghum.html (accessed 12 May 2019).

Derpsch, R., A.J. Franzluebbers, S.W. Duiker, D.C. Reicosky, K. Koeller, T. Friedrich, W.G. Sturny, J.C.M. Sa, and K. Weiss. 2014. Why do we need to standardize no-tillage research? Soil Till. Res., 137:16-22. doi:10.1016/j.still.2013.10.002.

Dhuyvetter, K.C., C.R. Thompson, C.A. Norwood, and A.D. Halvorson. 1996. Economics of dryland cropping systems in the Great Plains: A review. J. Prod. Agric. 9:216–222.

Dobberstein, J. 2014. U.S. No-Tilled Acres Reach 96 Million. No-till Farmer. Poster. https://www.no-tillfarmer.com/articles/2512-us-no-tilled-acres-reach-96-million (accessed 20 Nov. 2018).

Doran, J.W., and M.R. Zeiss. 2000. Soil health and sustainability: Managing the biotic component of soil quality. Appl. Soil Ecol. 15:3–11. doi:10.1016/S0929-1393(00)00067-6.

Doran, J.W., and T.B. Parkin. 1994. Defining and Assessing Soil Quality. In: Doran, J.W., Coleman, D.C., Bezdicek, D.F., and Stewart, B.A., Defining soil quality for a sustainable environment. SSSA Special Publication 35, Madison, WI. 1–21.

Erenstein, O., K. Sayre, P. Wall, J. Hellin, and J. Dixon. 2012. Conservation agriculture in maize- and wheat-based systems in the (sub)tropics: lessons from adaptation initiatives in

South Asia, Mexico, and Southern Africa. J. Sustain. Agric., 36:180-206. doi:10.1080/10440046.2011.620230.

European Commission. 2002. Communication of April 2002 from the Commission to the Council, the European Parliament, the Economic and Social Committee and the Committee of the Regions: towards a thematic strategy for soil protection [COM (2002) 179 final]. Brussels, Belgium: European Commission.

FAO. 2016. FAO Statistics. Food Agric. Organ. United Nations. http://www.fao.org/faostat/en/#data/QC (accessed 11 Sept. 2019).

FAO. 2011. FAO Statistics. Food Agric. Organ. United Nations. http://faostat3.fao.org/home/E%5Cnhttp://faostat3.fao.org/faostat-gateway/go/to/download/Q/QC/E%5Cnhttp://faostat3.fao.org/ (accessed 8 Feb. 2019).

Farooq, M., K.C. Flower, K. Jabran, A. Wahid, and K.H.M. Siddique. 2011. Crop yield and weed management in conservation agriculture. Field Crops Res., 117:172–183. doi:10.1016/j.still.2011.10.001.

Farvid, M.S., E. Cho, A.H. Eliassen, W.Y. Chen, and W.C. Willett. 2016. Lifetime grain consumption and breast cancer risk. Breast Cancer Res. Treat. 159:335–345. doi:10.1007/s10549-016-3910-0.

Foley, J., N. Ramankutty, K. Brauman et al. 2011. Solutions for a cultivated planet. Nature, 478:337–342. doi:10.1038/nature10452.

Foster, J.L., M.E. Bean, C. Morgan, G. Morgan, R. Mohtar, J. Landivar, and M. Young. 2018. Comparison of two tillage practices in a semi-arid cotton-grain sorghum rotation. Agron. J. 110:1572–1579. doi:10.2134/agronj2017.12.0706.

Foster, J.L., J.P. Muir, J.R. Bow, and E. Valencia. 2017. Biomass and nitrogen content of fifteen annual warm-season legumes grown in a semi-arid environment. Biomass and Bioenergy. 106:38-42.

Giller, K.E., E. Witter, M. Corbeels, P. Tittonell. 2009. Conservation agriculture and smallholder farming in Africa: the heretics' view. Field Crops Res., 114:23–34.

Gold, M.V. 1999. Sustainable Agriculture: Definitions and Terms. National Agriculture Library, USDA, Beltsville, MD. https://www.nal.usda.gov/afsic/sustainable-agriculture-definitions-and-terms (accessed 2 Sept. 2019).

Grünwald, N.J., S. Hu, and A.H.C. Van Bruggen. 2000. Short-term cover crop decomposition in organic and conventional soils: Characterization of soil C, N, microbial and plant pathogen dynamics. Eur. J. Plant Pathol. 106:37–50.

Haney, R.L. 2014. Soil health. USDA-ARS. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs144p2_043902.pdf (accessed 9 Sept. 2019).

Haney, R.L., A.J. Franzluebbers, V.L. Jin, M. Johnson, E.B. Haney, M.J. White, and R.D. Harmel. 2012. Soil organic C: N vs. water-extractable organic C: N. Open J. Soil Sci. 2:269–274. doi:10.4236/ojss.2012.23032.

Hay, R.K.M., J.C. Holmes, E.A. Hunter. 1978. The effects of tillage, direct drilling and nitrogen fertiliser on soil temperature under a barley crop. J. Soil Sci., 29:174–183.

Hinze, G.O., and D.E. Smika. 1983. Cropping practices: Central Great Plains. In: Dregne, H.E., Willis, W.O. (Eds.), Dryland Agriculture. Agron. Monogr. 23. ASA, CSSA, and SSSA, Madison, WI. 387–395.

Hobbs, P.R., K., K. Sayre, R. Gupita. 2007. The role of conservation agriculture in sustainable agriculture. Phil. Trans. R. Soc. B. 363:543 – 555. doi: 10.1098/rstb.2007.2169

Holland, J.M. 2004. The environmental consequences of adopting conservation tillage in Europe: reviewing of the evidence. Agriculture, Ecosystems and Environment 103:1 – 25.

Hussain, I., K.R. Olson, J.C. Siemens. 1998. Long-term tillage effects on physical properties of eroded soil. Soil Sci., 163:970–981.

Kahlon, M.S., R. Lal, and M. Ann-Varughese. 2013. Twenty two years of tillage and mulching impacts on soil physical characteristics and carbon sequestration in Central Ohio. Soil and Tillage Research. 126: 151–158.

Keeling, W., E. Segerra, and J.R. Abernathy. 1989. Evaluation of conservation tillage cropping systems for cotton on the Texas High Plains. J. Prod. Agric. 2:269–273.

Kibblewhite, M.G., K. Ritz, and M.J. Swift. 2008. Soil health in agricultural systems. Phil. Trans. R. Soc. B. 363:685-701 doi:10.1098/rstb.2007.2178.

Lal R. 2001. Soil degradation by erosion. Land Deg. Dev. 12: 519–539.

Lal, R. 1994. Sustainable land use systems and resilience. In Soil resilience and sustainable land use. Proc. Symp. held in Budapest, 28 September to 2 October 1992, including the Second Workshop on the Ecological Foundations of Sustainable Agriculture (WEFSA II) (eds D. J. Greenland & I. Szabolcs), 99–118. Oxford, UK: CAB International.

Langham D.R., J. Riney, G. Smith, T. Wiemers, D. Pepper, and T. Speed. 2010. Sesame Producers Guide. Sesaco Corp.

Lewis, K.L., J.A. Burke, W.S. Keeling, D.M. McCallister, P.B. DeLaune, and J.W. Keeling. 2018. Soil Benefits and Yield Limitations of Cover Crop Use in Texas High Plains Cotton. Agron. J. 110:1616 – 1623. doi:10.2134/agronj2018.02.0092.

Magdoff, F., and H. Van Es. 1993. Building Soils for Better Crops Sustainable Soil Management. Third Edition. http://faculty.washington.edu/elizaw/building%20Soils%20for%20better%20crops.pdf (accessed 11 Sept. 2019).

Massee, T.W., and J.W. Cary. 1978. Potential for reducing evaporation from summer fallow. J. Soil Water Conserv. 33:126-129. https://eprints.nwisrl.ars.usda.gov/337/1/403.pdf (accessed 6 July 2020).

Meyers, R.L. 2010. Sunflower: A Native Oilseed with Growing Markets. Jefferson Inst.https://trace.tennessee.edu/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=1016&context=utk_agexcrop (accessed 1 April 2019).

Mikkola, H.J., L. Alakukku, H. Känkänen, H. Jalli, M. Lindroos, E. Huusela-Veistola, V. Nuutinen, M. Lätti, M. Puustinen, E Turtola, M Myllys, R. Regina. 2005. Direct drilling in Finland, a review. Proc. 4th Intern. Scientific and Practical Conference, Ecology and Agricultural Machinery, May 25–26, 2005, St Petersburg, 2:141-151.

Moebius-Clune, B.N., D.J. Moebius-Clune, B.K. Gugino, O.J. Idowu, R.R. Schindelbeck, A.J. Ristow, H.M. van Es, J.E. Thies, and H.A. Shayler. 2016. Comprehensive Assessment of Soil Health (C University, Ed.). 3.1. Ithica.

Morris, J.B. 2002. Food, industrial, nutraceutical, and pharmaceutical uses of sesame genetic resources. In: J. Janick and A. Whipkey, eds., Trends in new crops and new uses. ASHS Press, Arlington, VA. 153– 156. https://hort.purdue.edu/newcrop/ncnu02/pdf/morris.pdf (accessed 16 Sept. 2019).

Myers, R. 2002. Alternative crop guide: Sesame. Jefferson Institute, Columbia, MO. https://www.extension.iastate.edu/alternativeag/cropproduction/pdf/sesame_crop_guide.pdf (accessed 16 Sept. 2019).

Nakajima, T., R.K. Shrestha, R. Lal, and C. Ideas. 2016. On-Farm Assessments of Soil Quality in Ohio and Michigan. SSSA. J. 80:1020–1026. doi:10.2136/sssaj2016.01.0003.

Neely et al. 2017. 2017 Texas Wheat Variety Trial Results. SCS-2017-10. http://varietytesting.tamu.edu/wheat/ (accessed 30 March 2019).

Newman, Y., E. Jennings, J. Vendramini, and A. Blount. 2014. Pearl Millet (*Pennisetum glaucum*): Overview and Nutritive Value. IFAS - Inst. Food Agric. Sci. - Univ. Florida: 1–5.

Nielsen, D.C., P.W. Unger and P.R. Miller. 2005. Efficient water use in dryland cropping systems in the Great Plains. Agron. J. 97:364–372.

Nielsen, D.C., M.F. Vigil, R.L. Anderson, R.A. Bowman, J.G. Benjamin, and A.D. Halvorson. 2002. Cropping system influence on planting water content and yield of winter wheat. Agron. J. 94:962–967.

Nielsen, D.C., R.L. Anderson, R.A. Bowman, R.M. Aiken, M.F. Vigil, and A.G. Benjamin. 1999. Winter wheat and proso millet yield reduction due to sunflower in rotation. J. Prod. Agric. 12:193–197.

Ogle, S.M., A. Swan, K. Paustian. 2012. No-till management impacts on crop productivity, carbon input and soil carbon sequestration. Agric. Ecosyst. Environ., 149:37–49.

Pittelkow, C.M., X Liang, B.A. Linquist, K.J. Van Groenigen, J. Lee, M.E. Lundy, N. Van Gestel, J. Six, R.T. Venterea, and C. van Kessel. 2015. Productivity limits and potentials of the principles of conservation agriculture. Nature 517:365–368.

Post, W.M., W.R. Emmanuel, P.J. Zinke, and A.G. Stangenberger. 1982. Soil carbon pools and world life zones. Nature 298:156–159.

Rao, S.C., and B.K. Northup. 2013. Biomass production and quality of indian-origin forage guar in Southern Great Plains. Agron. J. 105:945–950. doi:10.2134/agronj2012.0378.

Rao, S.C., and B.K. Northup. 2009. Capabilities of four novel warm-season legumes in the southern Great Plains: Biomass and forage quality. Crop Sci. 49:1096–1102. doi:10.2135/cropsci2008.08.0499.

Raper, R.L., D.W. Reeves C.W. Burmester, E.B. Schwab. 2000. Tillage depth, tillage timing, and cover crop effects on cotton yield, soil strength, and tillage energy. Appl. Eng. Agric., 16:379–385.

Riley, H., T. Børrensen, E. Ekeberg, T. Rydberg. 1994. Trends in reduced tillage research and practice in Scandinavia. M.R. Carter (Ed.), Conservation Tillage in Temperate Agroecosystems, Lewis Publishers, Boca Raton, Florida, USA. 23–45.

Rotar, P.P, and R.J. Joy. 1983. ‘Tropic Sun’ Sunn Hemp (*Crotalaria juncea* L.). Research Extension Series 036. 630 US ISSN 0271–9916. https://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/hipmcpu2531.pdf (accessed 16 Sept. 2019).

Rusinamhodzi, L., M. Corbeels, M. van Wijk, M.C. Rufinio, J. Nyamangara, K.E. Giller. 2011. A meta-analysis of long-term effects of conservation agriculture practices on maize yields under rain-fed conditions. Agron. Sustain. Dev., 31:657–673. doi:10.1007/s13593-011-0040-2.

SARE. 2012. Cowpeas. https://www.sare.org/Learning-Center/Books/Managing-Cover-Crops-Profitably-3rd-Edition/Text-Version/Legume-Cover-Crops/Cowpeas (accessed 31 March 2019).

Schlesinger, W.H. 1997. Biogeochemistry: An Analysis of Global Change. Academic Press, San Diego, CA. 588.

Shangning, J., and P.W. Unger. 2001. Soil Water Accumulation under Different Precipitation, Potential Evaporation, and Straw Mulch Conditions. SSSA J. 65. 10.2136/sssaj2001.652442x.

Singh, B.B. 2014a. Cowpea: The Food Legume of the 21st Century. CSSA, Madison, WI.

Singh, S.K. 2014b. An analysis of performance of guar crop in India. GAIN Rep. IN4035.USDA, New Delhi, India.

Singla, S., K. Grover, S.V. Angadi, S.H. Begna, B. Schutte, and D. Van Leeuwen. 2016a. Growth and yield of guar (*Cyamopsis tetragonoloba* L.) genotypes under different planting dates in the semi-arid Southern High Plains. Am. J. Plant Sci. 7:1246–1258. doi:10.4236/ ajps.2016.78120.

Singla, S., K. Grover, S.V. Angadi, B. Schutte, and D. VanLeeuwen. 2016b. Guar stand establishment, physiology, and yield responses to planting date in southern New Mexico. Agron. J. 108:2289–2300. doi:10.2134/agronj2016.04.0206.

Slavin, J. 2004. Whole grains and human health. Nutr. Res. Rev. 17:http://www.journals.cambridge.org/abstract_S0954422404000095 (accessed 15 Jan. 2019).

Soane, B.D., B.C. Ball, J.A. Arvidsson, G. Basch, and J. Roger-Estrade. 2012. No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. Soil and Tillage Res. 188:66 – 87. doi:10.1016/j.still.2011.10.015.

Soil Health Institute. 2016. National Soil Health Measurements to Accelerate Agricultural Transformation. https://soilhealthinstitute.org/national-soil-health-measurements-accelerate-agricultural-transformation/ (accessed 8 Feb. 2019).

Stone, L.R., and A.J. Schlegel. 2006. Yield-water supply relationships of grain sorghum and winter wheat. Agron. J. 98:1359–1366.

Tebrugge, F., and R.A. During. 1999. Reduced tillage intensity – a review of results from a long-term study in Germany. Soil & Tillage Research 53:15–28.

Tebrügge, F., W. Gruber, R. Kohl, H. Böhm. 1991. Long-term cultural practices effects on the ecologic system. Presented at International Summer Meeting, Paper No. 91-1009, Am. Soc. Agric. Engineers, St. Joseph, MI. 15.

Tejada, M., and C. Benitez. 2014. Effects of Crushed Maize Straw Residues on Soil Biological Properties and Soil Restoration. Land Degrad. Develop. 25:501–509.

Thorup-Kristensen, K. 2001. Are differences in root growth of nitrogen catch crops important for their ability to reduce soil nitrate-N content, and how can this be measured? Plant Soil 230:185–195.

Tripp, L.D., D.A. Lovelace, and E.P. Boring. 1982. Keys to profitable guar production. Texas Agric. Ext. Serv. Bull. B- 1399. Texas A&M University System, College Station, TX.

Unger P.W., W.A. Payne, G.A. Peterson. 2006. Water conservation and efficient use. In: G.A. Peterson et al., editors, Dryland Agriculture. 2nd ed. Agronomy Monograph No. 23. ASA-CSSA-SSSA, Madison, WI. 39—85.

Unger, P.W. 1984. Tillage and residue effects on wheat, sorghum and sunflower grown in rotation. Soil Sci. Soc. Am. J. 48:1423–1432.

USDA-NASS. 2018. National Statistics for Wheat. https://www.nass.usda.gov/Statistics_by_Subject/result.php?28A233C3-D688-31F0-9EF9-EE4AE8BB2D30&sector=CROPS&group=FIELD%20CROPS&comm=WHEAT (accessed 30 March 2019).

USDA-NASS. 2017. 2017 Census - Farms and Farmland. ACH17-3/August 2019. https://www.nass.usda.gov/Publications/Highlights/2019/2017Census_Farms_Farmland.pdf (accessed 11 Sept. 2019).

USDA-NASS. 2016. Crop Production 2015 Summary. ISSN: 1057–7823. https://www.usda.gov/nass/PUBS/TODAYRPT/cropan16.pdf (accessed 11 Sept. 2019).

USDA-NRCS. 2018. Cover Crops That Take Heat. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/plantmaterials/home/?cid=NRCSEPRD1449247 (accessed 30 March 2019).

USDA-NRCS. 2017. Cover crops and soil health. USDA-NRCS plant materials program. https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/plantmaterials/technical/publications/?cid=stelprdb1077238 (accessed 12 March 2019).

USDA-NRCS. 2014. Plant Guide SESAME. USDA-Natural Resources Conservation Services.

USDA-NRCS. 2012a. Effects of Mixed Species Cover Crop on Soil Health.

USDA-NRCS. 2012b. Lablab Plant Guide. : 2010–2012.

Van den Putte, A., G. Govers, J. Diels, K. Gillijns, M. Demuzerea. 2010. Assessing the effect of soil tillage on crop growth: a meta-regression analysis on European crop yields under conservation agriculture. Eur. J. Agron. 33:231–241.

van Es, H.M., and R.R. Schindelbeck. 2003. Field procedures and data analysis for the Cornell sprinkle infiltrometer. Cornell University. https://cpb-us-e1.wpmucdn.com/blogs.cornell.edu/dist/f/5772/files/2015/11/Cornell-Sprinkle Infiltrometer-manual-1xf0snz.pdf (accessed 18 Jan. 2019).

Van Ouwerkerk, C., U.D. Perdok. 1994. Experiences with minimum and no-tillage practices in the Netherlands. I: 1962-1971. F. Tebrügge, A. Böhrnsen (Eds.), Experience with the

Applicability of No-tillage Crop Production in the West-European Countries. Proc. EC-Workshop-I, Wissenschaftlicher Fachverlag, 35428 Langgöns, Germany. 59-67.

Weyers, S.L., K.A. Spokas. 2014. Crop residue decomposition in Minnesota biochar-amended plots. Solid Earth. 5:499–507.

Wong, L.J., and C. Parmar. 1997. *Cyamopsis tetragonoloba* (L.) Taubert. Record from Proseabase. In: I.F. Hanum and L.J.G. van der Maesen, editors, Plant resources of south-east Asia no. 11: Auxiliary plants. Backhuys Publishers, the Netherlands. 109–113.

CHAPTER II

CROPPING SYSTEMS DIVERSITY AND TILLAGE INTENSITY AFFECTS WHEAT PRODUCTIVITY IN TEXAS

2.1. Introduction

Healthy soil is capable of supporting the production of food and fiber to a level, and with a quality, sufficient to meet human requirements while delivering other ecosystem services that are essential for maintaining the quality of life for humans and conserving biodiversity (Doran and Zeiss, 2000; Kibblewhite et al., 2008). Management practices, such as tillage and crop rotation, can have significant impacts on soil organic carbon (OC) which is the major driver of soil health (Kibblewhite et al., 2008). For example, no tillage (NT) systems can build soil OC through slower decomposition of crop residues which enhances soil function (Tebrugge and During, 1999). Diverse crop rotations, including cover crops and double cropping, have been shown to magnify the beneficial impacts of reduced tillage and prevent soil erosion through ground coverage (Keeling et al., 1989; Magdoff and Van Es, 1993). In contrast, traditional management practices, such as fallow periods and conventional tillage (CT), over time can lead to degradation of soil and decline in productivity which may decrease long-term sustainability, economic viability, and consequently affect food production with a growing world population (Alexandratos and Bruinsma, 2012; Alvarez and Steinbach, 2009; Tebrugge and During, 1999).

Wheat (*Triticum* sp.) is one of the most sought-after agricultural products in the world and has been identified as one of the major sources of food supply and security due to its high-quality nutrition and health benefits especially in developing countries (FAO, 2011; Farvid et al., 2016; and Slavin, 2004). In 2020, 17.9 million hectares were planted in the United States; 1.98

million hectares were planted in Texas (USDA-NASS, 2020). The majority of wheat production systems in Texas are managed under CT and followed by three to nine months of fallow, leaving the soil without cover and increasing its susceptibility to erosion and evaporative water loss (Massee and Cary, 1978). Reduced tillage, and double cropping during the traditionally fallow period, may improve productivity, farmer's net return, and soil health in wheat cropping systems (Alexandratos and Bruinsma, 2012). Borchers et al. (2014) reported that only 2.1% of agricultural lands are utilized for double cropping in Texas.

No tillage has long been considered one of the most important management practices for sustainable cropping intensification to meet future global food demands (Derpsch et al., 2014) while preserving soil security by reducing soil erosion (Lal, 2001). In NT systems, residues left on the soil surface after crop harvest are a driving force for promoting microbial activity, accumulating OC and nutrients near the soil surface, improving aggregate stability, protecting against erosion, and increasing water infiltration rate (Tebrugge and During, 1999). No tillage has been shown to increase yields under water-limited environments (Farooq et al., 2011; Rusinamhodzi et al., 2011). However, studies have also shown NT practices resulted in low productivity because of possible soil water-logging and cooler soil temperatures, which can have negative impacts on crop stands (Anken et al., 2004; Hay et al., 1978; Riley et al., 1994; Soane et al., 2012; Van Ouwerkerk and Perdok, 1994). Other research indicates no difference between crop yield in NT or CT management (Foster et al., 2018). Dobberstein (2014) reported that only 8.8% of agricultural lands in Texas are used for NT farming. This ranks Texas poorly in the U.S. in terms of adoption of NT practices. No tillage combined with crop rotation and soil ground coverage or residue retention has been observed to reduce cost of production due to decreased energy and labor requirements, while increasing yields and profitability compared to CT agriculture system in the subtropics in South Asia, Mexico, and South Africa (Erenstein et al., 2012; Foley et al., 2011). In Texas, winter wheat and fall-planted spring wheat are harvested in May or June; therefore, selecting a summer crop that can handle heat and drought stress during Texas summers and will be harvested prior to wheat planting in November or December is key to ensuring wheat-summer double crop rotation functionality. Combining reduced tillage with summer double crop may have the potential to increase producer's annual revenue in Texas. We hypothesized that including summer double crops will not statistically reduce wheat grain, and herbage mass when compared to the summer fallow control. We also hypothesized that reduced tillage (NT and ST) will not statistically decrease wheat and double crops grain and herbage mass compared to CT. The overall objective of this study was to determine the effects of reduced tillage and double cropping on overall cropping system productivity across the South-Central U.S. The specific objectives include quantifying the impact of CT, NT, and strip-till (ST) as well as summer double-crops on (1) wheat crop establishment (2) wheat and double crop grain yield, and (3) wheat and double crop herbage mass in three agriculturally important ecoregions in Texas. Summer double-crops included a cover crop mixture, cowpea [*Vigna unguiculata* (L.) Walp], fallow, grain sorghum [*Sorghum bicolor* (L.) Moench], and sesame [*Sesame indicum* L.].

2.2. Materials and Methods

2.2.1. Experimental Sites and Weather

This study was conducted for five years (2016 to 2020) in three locations (Beeville, Lubbock, and Thrall, TX) that represented important agricultural ecoregions in Texas. The Beeville site was located at the Texas A&M AgriLife Research Station (28° 27'N 97° 42'W; 74 m elevation) in the Coastal Plains ecoregion which is a humid subtropical climate. The Beeville site soil type was classified as a Parrita sandy clay loam (loamy, mixed, superactive, hyperthermic, shallow Petrocalcic Paleustoll) (Soil Survey Staff, 2021). The Lubbock site was located at the Texas A&M AgriLife Research and Extension Center (33° 41'N 101° 49'W; 1001 m elevation) in the High Plains ecoregion which is a semi-arid temperate climate. The Lubbock site soil was classified as an Olton clay loam (fine, mixed, superactive, thermic Aridic Paleustolls) (Soil Survey Staff, 2021). The Thrall site was located at the Stiles Farm Foundation (30° 36'N 97° 18'W; 173 m elevation) in the Blackland Prairies ecoregion which is warm and temperate. Thrall soil was classified as a Burleson clay (fine, smectitic, thermic Udic Haplusterts) (Soil Survey Staff, 2021). The land use history in the three locations prior to this study were perennial peanut [*Arachis hypogaea*] for 25 years at the Beeville location, cotton [*Gossypium hirsutum*] for over 10 years (conventionally tilled) at the Thrall site, and conventional tillage cotton for more than 10 years at the Lubbock site. Data for monthly rainfall and average monthly temperature data were collected through the National Oceanic and Atmospheric Administration (NOAA, 2020) and are shown in Figure 2.1. In summary, Beeville site weather data was collected from the Beeville 5 NE, TX US station within 1.2 km from the experimental site. Thrall weather data was collected from Thrall 10.5 SSE, TX US station within 24.1 km from the site. Lubbock weather data was collected from Lubbock Preston Smith International Airport Station, TX US within 1.9 km from the site. Soil characteristics of all the three locations are reported in Table 2.1.

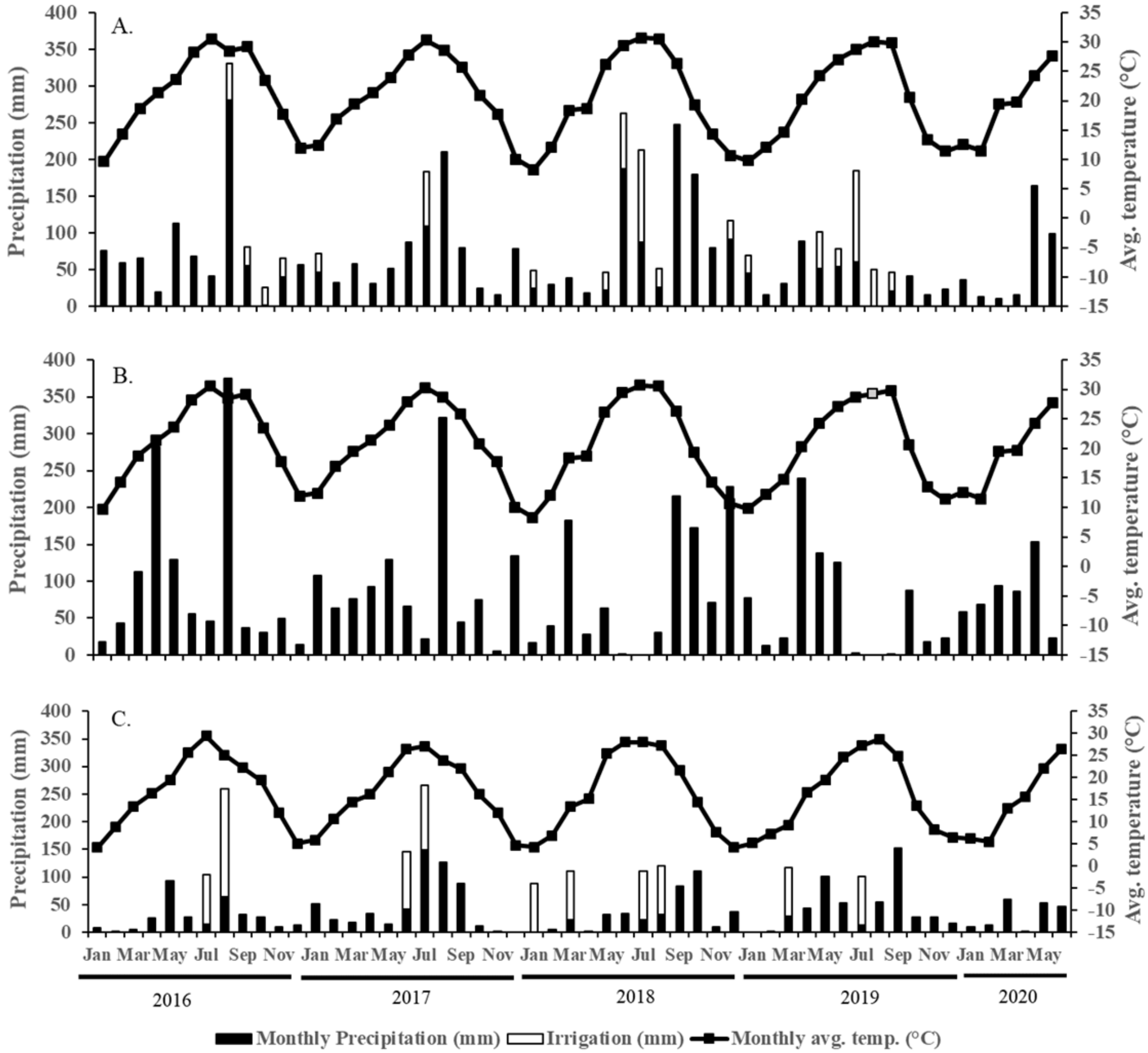

Figure 2.1. Average monthly temperature, precipitation, and irrigation during the experimental period at experimental sites in A. Beeville, B. Thrall, and C. Lubbock, Texas. Data point for Thrall for the month August 2019 was not available, thus, July and September average in 2019 was used.

Table 2.1. Soil characteristics of the three experimental sites (Beeville, Lubbock, and Thrall in Texas) determined at 0-15 cm soil depth.

Soil characteristics	Beeville	Lubbock	Thrall
Soil type	Parrita sandy clay loam	Olton clay loam	Burleson clay
Clay (g kg^{-1})	300	190	500
Silt (g kg^{-1})	170	300	280
Sand (g kg^{-1})	530	510	220
pH	7.1	7.7	5.4

Table 2.1. Continued

Soil organic carbon (%)	1.4	0.64	0.9
Bulk density (Mg m^{-3})	1.50	1.43	1.43

Source for soil texture, bulk density, was Soil Survey Staff, 2021; pH and soil organic carbon were reported from soils sampled in 2016.

2.2.2. Treatments and Experimental Design

The experimental design was a randomized complete block split-plot design with three replications used at all three locations. Treatments were randomly assigned to experimental units in 2016 (2015 for Thrall) and the same treatments imposed each year. The main plots were the tillage treatments (CT, NT, and ST), and the subplots were the summer double crop treatments (cover crop mixture, cowpea, grain sorghum, sesame, and fallow control). The cover crop mixture consisted of buckwheat [‘Mancan’, *Fagopyrum esculentum* Moench], cowpea ‘Iron and Clay’, guar [‘Kinman’, *Cyamopsis tetragonoloba* (L.) Taubert], lablab [‘Rio Verde’, *Lablab purpureus* (L.) Sweet] short stature sunflower [‘8H668S’, *Helianthus annuus* L.], pearl millet [*Pennisetum glaucum* (L.) R. Br.], sunn hemp [*Crotalaria juncea* L.], peanut ‘Tamrun OL 11’, and German foxtail millet [*Setaria italic* (L.) P. Beauv.]. Annual peanut and German foxtail millet were removed from the cover crop mixture in year three due to peanut incompatibility with the other cover crop species planting depth, and German foxtail millet poor stands. The experimental unit size at Beeville was 9.1 m long by 3.0 m wide, Lubbock was 12.2 m long by 4.1 m wide, and Thrall was 22.9 m by 7.6 m wide.

2.2.3. Cropping System Management

At Beeville and Thrall, conventional tillage plots were tilled at 15-cm depth using a disk Case IH 370 (Racine, WI, USA). At Beeville and Thrall, ST plots were tilled at 15-cm depth with an Orthman 1tRIPr (Lexington, NE, USA) with individual row spacing of 76 cm. At Beeville, a modified 1.5-m Great Plains NT drill was used to plant wheat throughout the study.

At Thrall, modified 1.5-m Great Plains NT drill was used to plant wheat (2015-2016, and 2019-2020), while a 3.7-m JD 8200 and Sunflower 9.1-m NT drill 9421 were used to plant wheat in 2017 and 2018 respectively at Thrall. Summer double crops were planted at Beeville and Thrall with John Deere Max Emerge Plus planter unit fitted with Almaco 31-cell cones for seed metering. It was a 2-row unit with adjustable row spacing. Conventional tillage received three passes, while ST received a single pass at both Beeville and Thrall. At Lubbock, CT plots were tilled with a John Deere tandem disk, model 630 with a 4.3-m width that runs 15 cm deep. Prior to listing in the CT each season it made two passes, one from each direction. For ST plots, the implement was an Orthman 1tRIPr that is 4 rows wide on 102 cm rows. Each individual strip was 30 cm wide and ran 8 cm deep with one pass made. The drill used for wheat planting was a Great Plains minimum till drill, model 1200, with a 3.7 m width and 19 cm spacing. The planter used for summer double crops was a John Deere Max Emerge plus 1700 that is 4-rows wide and used Almaco cones to plant the plots.

Wheat varieties for each location were selected based on their adaptability across regions and over the course of the study needed to be changed to address yield limiting issues such as poor vernalization at Beeville and Thrall, weed control at Thrall, and wheat streak mosaic virus at Lubbock. In Beeville, hard red winter wheat cultivar ‘TAM 304’ (Rudd et al., 2015) was planted in year one and was changed to hard red winter wheat cultivar ‘TAM 305’ (Ibrahim et al., 2015) in year two, and hard red spring wheat cultivar ‘LCS Trigger’ (Limagrain, Saint-Beauzire, Puy-de-Dôme, France) was planted for the final three seasons of the study. In Lubbock, ‘TAM 304’ was planted in the first two years of the study and was changed to hard red winter wheat cultivar ‘TAM 204’ (Rudd et al., 2019) in years three through five, though overall poor stands in year four required a replant using the spring wheat variety ‘LCS Trigger’. In

Thrall, hard red winter wheat cultivar ‘WB Cedar’ (Westbred, Fargo, ND, USA) was planted in the first two years, changed to hard red winter wheat cultivar ‘Gallagher’ (Marburger et al., 2021) in year three because of poor vernalization by WB Cedar, and LCS Trigger in year four and five to allow for later planting and better fall weed control. The row spacing for wheat planting was 19-cm for all three locations. In the ST treatment, the wheat crop was planted using NT, as tilled strips were wider than the row spacing for wheat.

The summer double crops were planted on a row spacing of 76 cm in Beeville and Thrall, and 102 cm row spacing for Lubbock in order to follow the typical row spacing practices in each ecoregion. All summer double crops, except sesame, were pre-treated with Apron XL fungicide (Mefenoxam, Syngenta, Greensboro, NC, USA), Cruiser 5FS insecticide (Thiamethoxam, Syngenta, Greensboro, NC, USA), and Dual safener. The cover crop mixture and the cowpea treatments were treated at the time of planting with a powdered Rhizobium species (N-DURE, Verdesian, Cary, NC, USA) inoculant to facilitate seed inoculation (Flynn, 2015). Wheat and summer double crop seeding rates in pure live seed (PLS), planting dates and harvest dates are detailed in Tables 2.2 and 2.3. Wheat fertilization was based on summer soil sample results and recommendations from the Texas A&M AgriLife Extension Service Soil, Water, and Forage Testing Laboratory (College Station, TX) (Table 2.4). Herbicide applications are detailed in Table 1 in supplementary data. Irrigation is presented as monthly totals in Figure 2.1. To avoid bird damage, wire mesh crop cages (1.5 m by 1.2 m) were installed across two center rows in each sorghum plot at all locations beginning in 2017 and in subsequent years.

Table 2.2. Planting date (planting), seeding rate (pure live seed [PLS] kg ha-1), and harvest date (harvest) for wheat and summer double crops included in the experiment for 2016 to 2020 for each location in Texas. Wheat was planted the end of the previous year.

Location	Crop	2016			2017			2018			2019			2020		
		Planting	PLS (kg ha^{-1})	Harvest	Planting	PLS (kg ha^{-1})	Harvest	Planting	PLS (kg ha^{-1})	Harvest	Planting	PLS (kg ha^{-1})	Harvest	Planting	PLS (kg ha^{-1})	Harvest
Beeville	Wheat	19 Nov (2015)	67		1 Dec (2016)	67	15 May	21 Nov (2017)	112	24 May	18 Dec (2018)	67	27 Apr	6 Dec (2019)	243	4 May
	Cover crop	9 Jun	49	25 Aug	8 Jun	50	13 Sep	29 May	35	12 Oct	11 Jul	33	23 Oct	-	-	-
	Cowpea	9 Jun	27	15 Aug	8 Jun	56	14 Aug	29 May	64	16 Nov	11 Jul	75	23 Oct	-	-	-
	Sesame	9 Jun	1.4	1 Nov	8 Jun	1.4	27 Oct	29 May	1.7	16 Nov	11 Jul	1.6	22 Nov	-	-	-
	Sorghum	28 Jun	3.7	1 Nov	17 Jul	4.9	3 Nov	29 May	5.1	12 Oct	11 Jul	4.9	23 Oct	-	-	-
Lubbock	Wheat	12 Dec (2015)	67	9 Jun	7 Dec (2016)	114	7 Jun	8 Dec (2017)	72	21 Jun	6 Feb (2019)	140	25 Jun	4 Dec (2019)	72	16 Jun
	Cover crop	20 Jun	49	26 Aug	14 Jul	50	12 Oct	28 Jun	35.0	10 Nov	25 Jul	33	4 Nov	-	-	-
	Cowpea	20 Jun	27	26 Sep	14 Jul	56	12 Oct	28 Jun	64	10 Nov	25 Jul	75	18 Oct	-	-	-
	Sesame	20 Jun	1.4	16 Nov	14 Jul	2.5	10 Nov	28 Jun	1.3	10 Nov	25 Jul	1.2	4 Nov	-	-	-
	Sorghum	20 Jun	3.7	24 Oct	14 Jul	4.1	10 Nov	28 Jun	4.3	10 Nov	25 Jul	4.6	4 Nov	-	-	-
Thrall	Wheat	2 Dec (2015)	79	13 May	15 Nov (2016)	79	28 May	18 Dec (2017)	90	18 May	31 Jan (2019)	118	3 Jun	18 Dec (2019)	108	14 May
	Cover crop	14 Jun	49	9 Sep, 12 Oct†	13 Jun	50	15 Sep	25 May	35	5 Sep	22-Jun	33	21 Oct	-	-	-
	Cowpea	14 Jun	27	9, 15 Sep	13 Jun	56	22 Sep	25 May	63	5 Sep	22 Jun	75	26 Sep	-	-	-
	Sesame	14 Jun	1.4	14 Nov	13 Jun	1.8	19 Oct	25 May	1.7	7 Nov	22 Jun	1.6	21 Oct	-	-	-
	Sorghum	14 Jun	3.7	12, 15, 22 Sep, 7 Oct	13 Jun	4.9	26 Oct	25 May	5.4	7 Nov	22 Jun	4.9	16 Oct	-	-	-

†Harvest made in different dates. Differences in maturity due to tillage treatments for summer double crops at Thrall in 2016.

Table 2.3. Cover crop cultivars included in the experiment for 2016 to 2019, their functional group classification, and their seeding rate of pure live seeds (PLS).

		Seeding rate (PLS), kg ha^{-1}			
Functional group	Species and cultivar	2016	2017	2018	2019
Legume	Cowpea, ‘Texas Pinkeye Purple Hull’	11.2	-	-	-
Legume	Cowpea, ‘Iron and Clay’		7.4	5.0	4.4
Legume	Guar, ‘Kinman’	1.2	1.3	1.8	1.9
Legume	Lablab, ‘Rio Verde’	3.6	3.3	6.2	5.8
Legume	Peanut, ‘Tamrun OL11’	14.6	19.3	-	-
Legume	Sunn Hemp	2.8	2.7	2.9	3.1
C_4 Grass	German Foxtail Millet	1.6	1.6	-	-
C_4 Grass	Pearl Millet Hybrid	4.9	4.9	5.7	5.0
C_3 Broadleaf	Sunflower, ‘8H668S’	1.2	1.3	1.7	1.5
C_3 Broadleaf	Buckwheat, ‘Mancan’	7.6	7.6	11.9	11.4

Table 2.4. Fertilizer applications by crop for 2016, 2017, 2018, 2019, and 2020 for each location.

				Nutrient (kg ha^{-1})			
Year	Crop	Form of fertilizer	Date applied	N	P_2O_5	K_2O	S
			Beeville				
2016	Wheat	Urea, TSP, K_2O	3 Feb	84.0	31.4	9.5	-
	Cover crop			-	-	-	-
	Cowpea	TSP	1 Jul	-	39.2	-	-
	Sesame	Ammonium sulfate, urea	1 Jul	33.6	61.6	-	26.9
	Sorghum	ammonium sulfate, urea	1 Jul	33.6	39.2	-	26.9
2017	Wheat	Urea, TSP	2 Jan	84.0	52.6	-	-
	Cover crop			-	-	-	-
	Cowpea			-	-	-	-

Table 2.4. Continued

	Sesame	UAN	14 Jun	84.0	-	-	-
	Sorghum	UAN	14 Jun	62.7	-	-	-
2018	Wheat	UAN, TSP	25 Jan	84.0	-	-	-
	Cover crop			-	-	-	-
	Cowpea	TSP	1 Jun	-	67.0	-	-
	Sesame	UAN, TSP	1 Jun	38.0	84.0	-	-
	Sorghum	UAN, TSP	1 Jun	38.0	84.0	-	-
2019	Wheat	Urea, TSP	22 Jan	84.0	56.0	-	-
	Cover crop			-	-	-	-
	Cowpea	TSP	21 Jun	8.0	56.0	-	-
	Sesame	Urea	21 Jun	89.0	56.0	-	-
	Sorghum	Urea	21 Jun	89.0	56.0	-	-
2020	Wheat	Urea, TSP	17 Jan	90.0	53.0	-	-
	Lubbock						
2016	Wheat	UAN	Mar	127.2	-	-	-
	Cover crop			-	-	-	-
	Cowpea			-	-	-	-
	Sesame		Jul	43.8	-	-	-
	Sorghum		Jul	79.5	-	-	-
2017	Wheat	UAN	Mar	127.3			
	Cover crop			-	-	-	-
	Cowpea			-	-	-	-
	Sesame			-	-	-	-
	Sorghum			-	-	-	-
2018	Wheat	UAN	21 Mar	117.7	-	-	-
	Cover crop			-	-	-	-
	Cowpea			-	-	-	-
	Sesame	Urea	11 Jul	16.8	-	-	-
	Sorghum	Urea	11 Jul	16.8	-	-	-
2019	Wheat	-		-	-	-	-
	Cover crop	-		-	-	-	-
	Cowpea	-		-	-	-	-
	Sesame	-		-	-	-	-
	Sorghum	-		-	-	-	-
2020	Wheat	-		-	-	-	-
	Thrall						
2016	Wheat	UAN	26 Jan	78.5	-	-	-
	Cover crop	7-21-2	19 Jul	16.4	49.2	4.7	-
	Cowpea	7-21-2	19 Jul	16.4	49.2	4.7	-
	Sesame	7-21-2, UAN	19 Jul	60.8	65.2	5.4	-
	Sorghum	7-21-2, UAN	19 Jul	60.3	30.0	2.6	-
2017	Wheat	UAN	16 Dec	80.7	-	-	-

Table 2.4. Continued

	Cover crop			-	-	-	-
	Cowpea	Potash, TSP	11 Jul	-	44.9	78.4	-
	Sesame	UAN, potash, TSP	11 Jul	81.8	44.9	78.4	-
	Sorghum	UAN, potash, TSP	11 Jul	76.2	44.9	78.4	-
2018	Wheat			-	-	-	-
	Cover crop			-	-	-	-
	Cowpea	TSP	14 Jun	-	50.4	-	-
	Sesame	UAN, TSP	14 Jun	72.9	50.4	-	-
		UAN, TSP					
	Sorghum		14 Jun	84.1	50.4	-	-
2019	Wheat	UAN, TSP		-	-	-	-
	Cover crop	UAN, TSP		-	-	-	-
	Cowpea	UAN, TSP	30 Jun	11.2	56.0	-	-
	Sesame	UAN	30 Jun	78.5	56.0	-	-
	Sorghum		30 Jun	95.3	56.0	-	-
2020	Wheat		30 Jan	100.9	-	-	-

[a] TSP triple superphosphate, UAN urea ammonium nitrate. At Beeville, all fertilizers were broadcast. At Lubbock, UAN was diluted with water at 1:1 ratio, and double crops fertilized with sidedress application (4-row). At Thrall, wheat liquid fertilizer application, and double crops N applied with sidedress (4-row); P and K was broadcast.

2.2.4. Response Variables

The response variables considered for this research were 1) wheat stand count, 2) wheat grain yield, 3) summer double crop (grain sorghum, sesame, and cowpea pulse) grain or pulse yield, and 4) wheat and summer double crop herbage mass.

2.2.4.1. Stand Count and Yield

Wheat stand counts were taken approximately three weeks after emergence in four (Beeville and Lubbock) or six (Thrall) random locations taken from the center four rows in each plot. The number of plants were counted in a 1-m length of row at each location within the plot. Wheat herbage mass subsamples were taken before combine harvest by hand clipping a 1-m^2 area to 5-cm stubble height from within the center of the plot. Wheat heads were separated from the herbage mass and samples dried in a forced-air oven at 50° C to a constant weight. Dried head samples were weighed initially before being threshed (Almaco LPR thresher, Nevada, IA). Following threshing, grain weight was subtracted from the initial head weight and the difference, which represented the head non-grain herbage mass, was added to the herbage sample to calculate total above-ground herbage mass. Harvesting of wheat grain was performed using a Wintersteiger (Wintersteiger Ag, Ried, Austria) classic plot combine (1.5 m header) for all locations. All summer double crops were harvested by hand in 1-m row length of the two center rows and were dried at 50° C in a forced air oven until constant weight and then weighed for above ground herbage mass estimate. The dried and weighed sorghum (heads), sesame (pods), cowpea (pods) samples were then threshed. Following threshing, the grain (sorghum), seed (sesame), and pulse (cowpea) weights were subtracted from the head (sorghum) and pod (cowpea and sesame) weights and the difference, which represented the head and pod chaff weights were added to the herbage sample to calculate total above-ground herbage mass. Test weight and moisture was performed using a Dickey John Model GAC 2100 (Dickey-John, Minneapolis, MN) to standardize sorghum grain yields to 78.9 kg hL^{-1} and 13.5% moisture. Cover crop herbage mass was measured by hand clipping two row lengths (1-m) within the two center rows. Samples were dried in a forced-air oven at 50°C until constant weight. Dried samples were weighed for herbage mass calculation.

2.2.5. Statistical Analysis

Wheat stand count and all grain and herbage mass yields were analyzed using PROC GLIMMIX in SAS (SAS Institute, 2010). Year was significant for all dependent variables at all locations, so data were analyzed within year and location. Treatments (tillage and crop) and their interaction were considered fixed effects; block and block x tillage were considered random effects. Location was analyzed separately because each location represented a different ecoregion. Additionally, data were missing for some crops at different locations in certain years due to bird damage or crop failure, and thus locations could not be combined. The LSMEANS function with the DIFF option was used to determine mean separation among significant effects. Statistical analysis results were considered significant if $P \leq 0.05$.

2.3. Results and Discussion

2.3.1. Wheat

A significant year x tillage and year x crop interaction for wheat stand, wheat grain yield, and wheat herbage mass was detected at all three locations (Tables 2.5) except for wheat stand count (year x double crop) and wheat herbage mass (year x tillage) in Beeville. The wheat stand count at Beeville was approximately 35 and 43% greater for conventional tillage over NT and ST in 2017 and 2019, respectively (Figure 2.2a). Summer double cropping did not affect wheat stand establishment throughout this study at Beeville (Table 2.5, Figure 2.3a). At Lubbock, tillage impact on wheat establishment was inconsistent across years with ST (166 plants m^{-2}) producing greater stands than CT (149 plants m^{-2}) and NT (149 plants m^{-2}) in 2017, while CT was greater than NT and ST in 2019 and 2020 (Figure 2.2d). Summer double cropping at Lubbock affected wheat stand establishment in one of four years and was greater in cover crop (120 plants m^{-2}) and sorghum (113 plants m^{-2}) treatments and least in fallow (87 plants m^{-2}) and cowpea (90 plants m^{-2}) treatments in 2020 (Figure 2.3d). At Thrall, NT (95 plants m^{-2}) and ST (91 plants m^{-2}) were greater than CT (78 plants m^{-2}) in 2016, while CT was greater than NT and ST in 2017 and 2020 (Figure 2.2g). Summer double cropping also affected wheat stand establishment at Thrall in 2017, 2019, and 2020 (Figure 2.3g). In 2017, wheat stand establishment was greater in cover crop (89 plants m^{-2}) treatment and least in fallow (68 plants m^{-2}) and sorghum (70 plants m^{-2}) treatments (Figure 2.3g). In 2019, cover crop and cowpea had the least wheat stands while in 2020 wheat stand establishment was greatest in the sorghum (119 plants m^{-2}) treatment and least in cowpea (103 plants m^{-2}), cover crop (107 plants m^{-2}), and fallow (107 plants m^{-2}) treatments. On average cowpea and cover crop rotations resulted in the lowest wheat stand establishment at Thrall. In general, wheat stands tended to correlate with seeding rates within a particular location, though environmental factors also played a role (Table 2.2). For example, below average rainfall occurred in Lubbock from Oct. 2017 to Feb. 2018 (Figure 2.1c), thus, low soil moisture likely reduced wheat crop establishment. The management practices evaluated in this study are unlikely to result in poor stands, depending on the environment, planting conditions, and importantly having the proper equipment to get good seed-soil contact if implementing reduced tillage in order to achieve adequate wheat emergence. Other studies reported no differences between NT and CT (Ahmad Khan et al., 2008; Lithourgidis et al., 2006; Schillinger, 2001; Wilkins et al., 1989). Hemmat and Eskandari (2006) found greater wheat stands in NT compared to the other tillage systems (CT and reduced tillage) and was consistent with our findings in 2016 at Thrall.

Wheat grain yield at Beeville was not affected by tillage throughout the study (Table 2.5, Figure 2.2b). Summer double cropping affected wheat grain yield in one out of the three years of study at Beeville (Table 2.5, Figure 2.3b). Sorghum treatment consistently produced the lowest wheat grain yield each year, though it was only significantly worse than the fallow treatment in 2020 along with all other double crop treatments that year (Figure 2.3b). At Lubbock, tillage affected wheat grain yield in one out of four years, and was greatest in CT (1895 kg ha^{-1}) and least in NT (729 kg ha^{-1}) and ST (815 kg ha^{-1}) in 2019 (Table 2.5, Figure 2.2e). Summer double cropping affected wheat grain yield in two out of four years at Lubbock.

Sorghum had the least wheat grain yield compared to cover crop and sesame in 2017, while in 2020, sorghum had the greatest wheat grain yield compared to all other treatments (Figure 2.2e). At Thrall, tillage and summer double cropping affected wheat grain yield in three out of six years. No tillage (3,931 kg ha^{-1}) and ST (4,030 kg ha^{-1}) were greater than CT (3,433 kg ha^{-1}) in 2016, while CT was greater than NT and ST in 2017 and 2019 (Figure 2.2h). Summer double cropping did not reduce wheat grain yield throughout this study at Thrall except the sorghum and cover crop treatments in 2018 (Figure 2.3h). In fact, sorghum and sesame improved wheat grain yield over the fallow control in 2019 and 2020. Poor vernalization (due to mild winter temperatures) occurred in 2017 at Thrall; while delayed wheat planting in 2019 (due to persistent rains) contributed to the overall lower wheat grain yields in those two years at Thrall (Fig. 2.1b and Table 2.2). At Beeville, there was no wheat grain yield to harvest in 2017 due to incomplete vernalization. The low wheat yield recorded in 2018 at Lubbock was mainly due to low in-season precipitation, (Fig. 2.1c) (Matsi et al., 2003; Lithourgidis et al., 2005).

In many cases, wheat grain yield followed similar patterns as wheat stand establishment (Beeville in 2019; Lubbock all years; Thrall most years). In general, wheat grain yield did not follow the same trend as wheat stand establishment for tillage at Beeville. At Lubbock, tillage impact on wheat grain yield followed the same trend as wheat stand establishment in 2019, while summer double cropping effect on wheat grain yield only followed the same trend as wheat stand establishment in 2020. Tillage impact on wheat grain yield was consistent with wheat stand establishment in 2016 and 2017 at Thrall, while summer double cropping effect on wheat grain yield did not follow the same trend as wheat stand establishment. In general, wheat grain yield at Lubbock was comparable between CT and NT in most year, while summer double cropping did not significantly reduce wheat grain yield in any year. At both Lubbock and Thrall, when tillage impacted wheat stand, it often led to a similar trend in wheat grain yield. Hence, good stand establishment is key to ensuring wheat productivity at these sites, though other factors can be equally as important such as planting date. Ultimately, our five-year study showed that summer double cropping in wheat production systems rarely had a negative impact on wheat production compared to the summer fallow check at all three sites. Certain double crops decreased wheat yield in two site-years while they increased wheat yield in three other site-years. Tillage impacts on wheat grain yield were less certain, but based on our experience with sorghum at Thrall reduced tillage may prove more reliable with proper equipment and residue management. For instance, shredding residues will increase the amount of residues on the ground, which can result in poor seed-soil contact, thus low wheat stand establishment. Other studies reported no significant impact of tillage on wheat grain yield (De Vita et al., 2007; Izaurralde et al., 1986; Norwood et al., 2013; Schillinger, 2001; Soane et al., 2012); however, some researchers have found significant differences between CT and NT in certain environments (De Vita et al., 2007; Hemmat and Eskandari, 2006; Norwood et al., 2013; Rothrock, 1987) due to greater soil water content under NT during precipitation events, which can negatively impact speed and uniformity of crop emergence compared to CT. For crop rotation systems, Rothrock (1987) found no differences in wheat grain yield between wheat-soybean double cropping and wheat monoculture in Pike County, GA. In Tribune, KS, Norwood et al. (2013) reported no significant difference for wheat grain yield between wheat-fallow, and wheat-sorghum-fallow crop rotation systems in most of the years of the study.

Treatment effects on wheat herbage mass differed by year and was inconsistent across locations. The wheat herbage mass at Beeville was not significant for tillage (Table 2.5, Figure 2.2c). Summer double cropping reduced wheat herbage mass at Beeville in one of four years and was greatest in fallow in 2020 (Figure 2.3c). At Lubbock, wheat herbage mass response to tillage was inconsistent across years and was greater in NT (3,836 kg ha^{-1}) and ST (3,771 kg ha^{-1}) than CT (2,612 kg ha^{-1}) in 2018, while CT (3,951 kg ha^{-1}) was greater than NT (2,276 kg ha^{-1}) and ST (2,040 kg ha^{-1}) in 2019 (Figure 2.2f). The grain sorghum treatment had the least wheat herbage mass in 2017 and greatest wheat herbage mass in 2020 (Figure 2.3f) while the other double crop treatments were never significantly different from the fallow control in any year at Lubbock. At Thrall, tillage significantly impacted wheat herbage mass in only one out of four years, which was due to greater wheat herbage mass in CT (3,449 kg ha^{-1}) and ST (3,226 kg ha^{-1}) treatments compared to NT (2,382 kg ha^{-1}) in 2017 (Figure 2.2i). However, conventional tillage numerically resulted in greater wheat herbage mass in every year at Thrall. Statistically, grain sorghum (2017 and 2018) and cover crop (2018) were the only double crop treatments that reduced wheat herbage mass in any year at Thrall (Figure 2.3i). These double crops produced the most summer biomass which may have tied up nutrients that limited wheat herbage production and in some cases reduced wheat stands because of poorer seed-soil contact from abundant residue at planting. Overall, low wheat herbage mass recorded in 2017 at Beeville and Thrall was due to poor vernalization of the winter wheat cultivar used and limited jointing that occurred from not meeting the minimum chilling requirement from the mild winter. Poor stands at Lubbock in fall 2018 (2019 crop) necessitated a late replanting using spring wheat which contributed to the low wheat herbage mass that year (Table 2.2). In general, wheat herbage mass followed very similar response to tillage and summer double crop treatments as wheat grain yield, which is not unexpected (Figure 2.2). The relationship between wheat herbage mass and wheat stand count based on summer double crop treatments was not as consistent. Mrabet (2000) found no differences between NT and CT for wheat herbage mass in a four-year study. However, other researchers reported contradicting results; Hemmat and Eskandari (2006) reported greater wheat herbage mass for NT than CT and suggested greater yield in NT was due to increased capacity to store soil moisture and was consistent with our findings in 2018 at Lubbock. Hajabbasi (2003) also reported greater wheat herbage mass yield during drought years for NT.

Based on these results, summer double cropping shows limited negative, and in some cases positive, impacts on wheat grain production in all three ecoregions, which is an important consideration if planning to replace summer fallow with cover crops or double crops. The impacts of implementing reduced or no-till practices on wheat grain yield were quite variable across years at each location. In many, but all cases, impacts on yield could be attributable to tillage impacts on stand establishment. Proper equipment and residue management may alleviate some of the challenges with adopting reduced or NT systems for successful wheat production.

Table 2.5. ANOVA summary of significance as impacted by tillage, summer double cropping, and tillage x summer double cropping interaction for wheat stand count, grain yield, and herbage mass at Beeville, Lubbock, and Thrall in Texas from 2016 – 2019.

	Beeville														
	Wheat														
	Stand count (plants m^{-2})					Grain yield (kg ha^{-1})					Herbage mass (kg ha^{-1})				
Effect	2016	2017	2018	2019	2020	2016	2017	2018	2019	2020	2016	2017	2018	2019	2020
Tillage	-	*	NS[a]	***	NS	-	-	NS	NS	NS	-	NS	NS	NS	NS
Double crop	-	NS	NS	NS	NS	-	-	NS	NS	***	-	NS	NS	NS	***
Tillage x Double crop	-	NS	NS	NS	NS	-	-	NS	NS	NS	-	NS	NS	NS	NS
SEM	-	10	56	7	43	-	-	105	289	369	-	235	369	579	553
n	-	45	45	45	45	-	-	45	45	45	-	45	45	45	45
	Lubbock														
Tillage	-	**	NS	***	*	-	NS	NS	**	NS	-	NS	*	*	NS
Double crop	-	NS	NS	NS	*	-	*	NS	NS	**	-	*	NS	NS	**
Tillage x Double crop	-	NS	NS	NS	NS	-	NS	NS	NS	NS	-	NS	NS	NS	NS
SEM	-	6	9	12	12	-	186	65	170	447	-	219	224	423	817
n	-	45	45	45	45	-	41	39	42	45	-	45	39	44	45
	Thrall														
Tillage	***	*	NS	NS	*	**	*	NS	*	NS	-	*	NS	NS	NS
Double crop	NS	*	NS	**	*	NS	NS	***	***	*	-	***	***	***	NS
Tillage x Double crop	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	-	NS	NS	NS	NS
SEM	5	15	16	8	17	92	198	169	87	247	-	333	531	470	815
n	44	45	45	45	45	45	43	30	45	45	-	45	30	45	45

*, **, ***, Significant at the 0.05, 0.01, and 0.001 probability levels, respectively; [a]NS, not significant; SEM, standard error of mean; n, number of observations used.

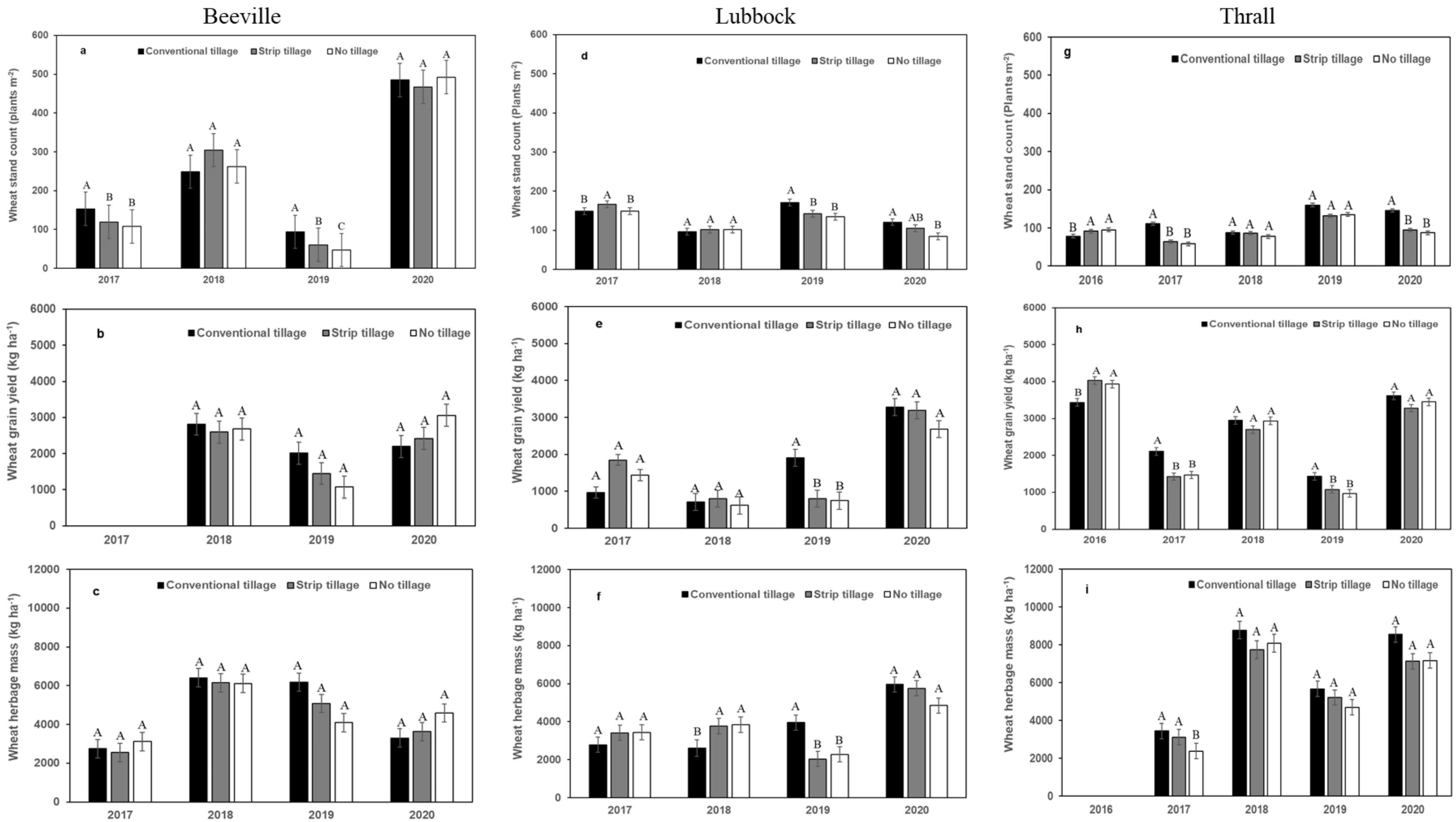

Figure 2.2. Wheat stand establishment (plants/m^2), wheat grain yield (kg ha^{-1}) and wheat herbage mass (kg ha^{-1}) as affected by tillage at Beeville, Lubbock, and Thrall locations in Texas from 2016 - 2020. Bars represent standard error of mean, and different letters within each year at each location are significant (P < 0.05).

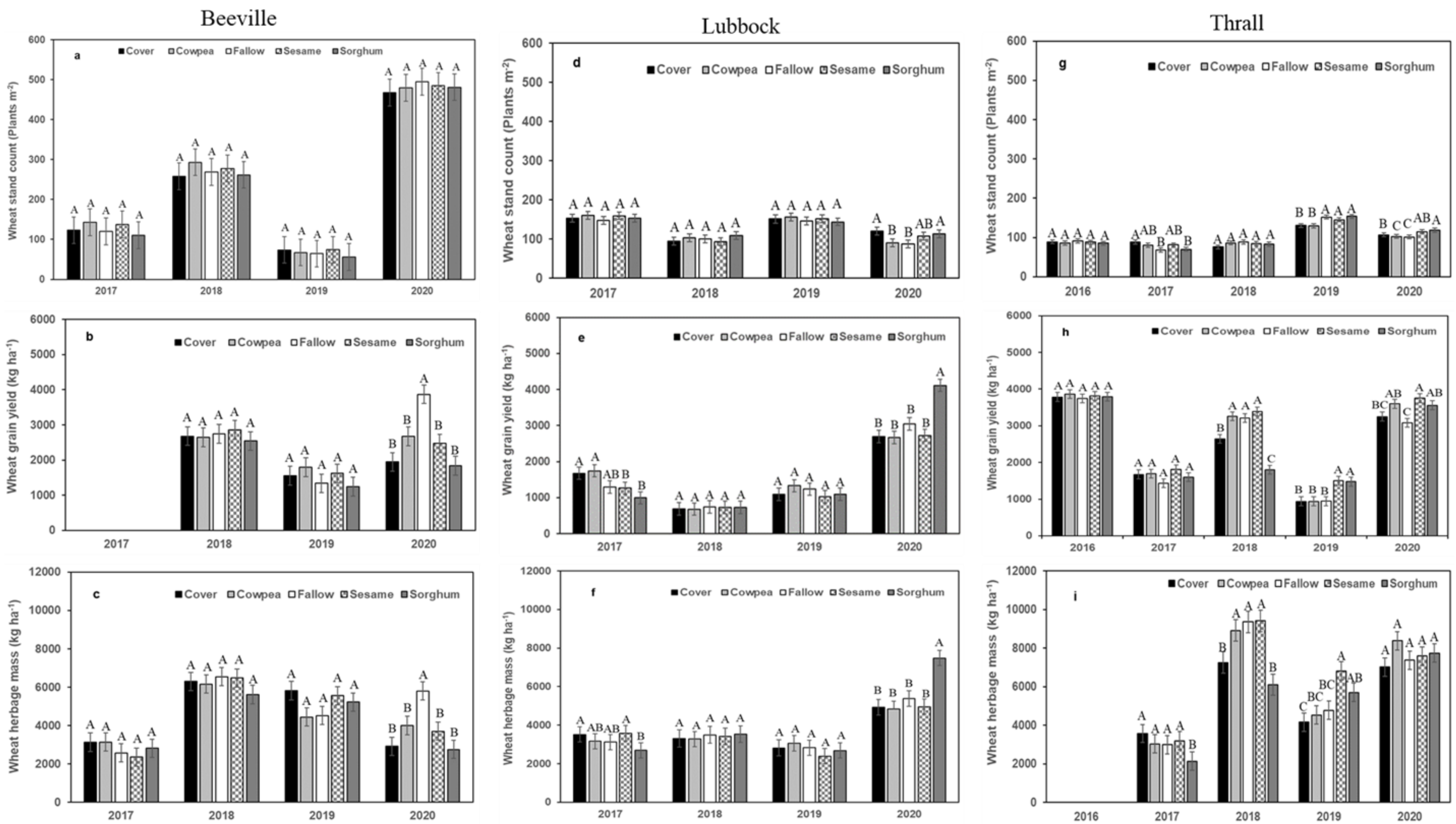

Figure 2.3. Wheat stand establishment (plants m^{-2}), wheat grain yield (kg ha^{-1}) and wheat herbage mass (kg ha^{-1}) as affected by summer double cropping at Beeville, Lubbock, and Thrall locations in Texas from 2016 – 2020. Bars represent standard error of mean, and different letters within each year at each location are significant ($P < 0.05$).

2.3.2. Summer Double Crops

Cowpea pulse was harvested at Beeville, Lubbock, and Thrall locations for 2016, 2017, and 2019. There was no cowpea pulse harvest in 2018 due to insect damage and wildlife grazing in all three locations. Sesame seed yield was harvested at all years and locations except for Lubbock in 2017 when the sesame seed did not mature prior to the first killing frost event at Lubbock. Sorghum grain yield was harvested at all years and locations except for Beeville in 2016 due to bird damage.

Tillage affected cowpea pulse yield at Thrall only in 2017 (Table 2.6, Figures 2.4g). At Thrall cowpea pulse yield was greater in NT (517 kg ha^{-1}) than CT (234 kg ha^{-1}) and ST (198 kg ha^{-1}) treatments in 2017 (Figure 2.4g). Numerically, CT produced the highest pulse yield every year at Lubbock. Tillage affected sesame seed yield at Beeville (2016 and 2017), and Thrall (2019) (Table 2.6, Figures 2.4b, e, and h). Tillage did not impact sesame seed yield at Lubbock (Figure 2.4e). At Beeville, sesame seed yield was least in NT in 2016 and 2017 (Figure 2.4b), though ST was not significantly different from CT in either year. At Thrall, sesame seed yield was significantly greater in NT (1157 kg ha^{-1}) than CT (920 kg ha^{-1}) in 2019 only (Figure 2.4h); however CT was numerically always the lowest yielding tillage treatment at Thrall. Sorghum grain yield was not significantly affected by tillage at Beeville and Lubbock (Table 2.6, Figures 2.4c and f) throughout this study, though there was a strong trend of higher yields in the NT and lower yields in ST at Lubbock. The NT (8102 kg ha^{-1}) and ST (7803 kg ha^{-1}) treatments produced significantly higher sorghum grain yield at Thrall compared to CT (3164 kg ha^{-1}) in one out of four years.

Akinyemi et al. (2003) found no significance difference between CT and NT for cowpea pulse yield and was consistent with our results at Beeville and Lubbock. In contrast, other researchers reported greater cowpea pulse yield for CT compared to NT (Adekalu and Okunada, 2006; Aikins and Afuakwa, 2010). Adekalu and Okunada (2006) observed an increase in cowpea pulse yield for reduced tillage and CT compared to NT for each additional water application. Weed control was particularly challenging for sesame and may have resulted in lower yields in some years; however, Thrall yields in particular were similar to or exceeded commonly achieved yields in the Blacklands Prairie ecoregion for earlier plantings. In addition, late summer precipitation events may have contributed to the low sesame seed yields experienced in 2017 at Beeville (328 kg ha^{-1}) (Figure 2.4b) and 2018 at Thrall (758 kg ha^{-1}) (Figure 2.4h) (Figure 2.1a and c). In 2017, Hurricane Harvey played a significant role in reduction of sesame seed yield with heavy precipitation (142 mm) resulting in prolonged soil saturation and observed plant death at the Beeville research location. Late season precipitation has been suggested to negatively affect sesame plants after the late bloom development stages (Langham et al., 2010; Sheahan, 2014).

Low sorghum grain yield reported at Beeville (1714 kg ha^{-1}) in 2018 was mainly due to bird damage. The low sorghum grain yield in 2019 at Lubbock (921 kg ha^{-1}) was mainly due to delayed planting because the previous wheat crop was replanted and delayed wheat harvest. The sorghum variety was changed to an earlier maturing cultivar to compensate for a shorter growing season and ensure maturation before the first killing frost but yield still suffered. Thrall had low in-season rainfall (31 mm) from June of 2018 through August of 2018 resulting in lower sorghum grain production (1733 kg ha^{-1}) in 2018. While timely planting is critical to ensure maturation of grain sorghum (and sesame) before the first killing frost at Lubbock, this was not a concern at Thrall or Beeville which experience much longer growing seasons.

Researchers reported no differences between CT and NT for sorghum grain yield (Foster et al., 2018; Franzluebbers et al., 1995; Sow et al., 1997), which was consistent with our study at Beeville and Lubbock. Studies have shown crop residues under NT systems increased water storage capacity in the soil compared to CT system and may have improved yields in the NT system at Thrall (Baumhardt et al., 1985; Foster et al., 2018; Shaver et al., 2002; Sow et al., 1997).

Cover crop herbage mass was affected by tillage at Lubbock and Thrall in 2016 and 2018 respectively (Table 2.6, Figures 2.5e and i). At Lubbock, cover crop herbage mass was greater in NT (4576 kg ha^{-1}) and CT (4160 kg ha^{-1}) than the ST (1325 kg ha^{-1}) treatment in 2016. At Thrall, cover crop herbage mass greater in NT (2637 kg ha^{-1}) than ST (1554 kg ha^{-1}) and CT (1041 kg ha^{-1}) in 2018. Tillage did not affect cover crop herbage mass at Beeville throughout this study (Table 2.6, Figure 2.5a). Cowpea herbage mass was not affected by tillage at Beeville throughout this study (Table 2.6, Figure 2.5b). Tillage did not affect cowpea herbage mass at Lubbock and Thrall (Table 2.6, Figures 2.5f and j) throughout this study.

Sesame herbage mass was affected by tillage at Beeville, Lubbock, and Thrall (Table 2.6). At Beeville, tillage impact on sesame herbage mass was inconsistent; in 2017, ST (1574 kg ha^{-1}) and CT (1332 kg ha^{-1}) were greater than NT (609 kg ha^{-1}), while in 2018, NT had the greatest sesame herbage mass (Figure 2.5c). At Lubbock, sesame herbage mass greater in ST (2547 kg ha^{-1}) than CT (1701 kg ha^{-1}) and NT (1716 kg ha^{-1}) (Figure 2.5g). At Thrall, sesame herbage mass was significantly greatest in NT and least in CT in 2017 and 2019 (Figure 2.5k) and were also numerically higher in NT and ST compared to CT in 2016 and 2018 as well.

Sorghum herbage mass was affected by tillage at Beeville (2017 and 2019) and Thrall (2019) (Table 2.6). At Beeville, sorghum herbage mass was greater in NT and CT than ST in both years (Figure 2.5d). At Thrall, sorghum herbage mass was greatest in NT (8211 kg ha^{-1}) and least in CT (5707 kg ha^{-1}) (Figure 2.5l). Tillage did not affect sorghum herbage mass at Lubbock throughout this study (Table 2.6, Figure 2.5h).

In the multi-species cover crop, pearl millet and ‘Iron and Clay’ cowpea were the most reliable species across all three locations, both in terms of establishment and herbage mass yield (Tables 2.7 and 2.8). Buckwheat, guar, and sunn hemp established stands well at Lubbock, while sunflower was second only to pearl millet in terms of herbage mass yield in all but one year where it produced more herbage mass. Lablab also did reasonably well at producing herbage mass each year at Thrall, though not as much as cowpea or pearl millet. Based on these results, pearl millet and ‘Iron and Clay’ cowpea are likely to be good additions to cover crops mixtures in the environments studied. Irrigation applied at Lubbock prior to planting provided a more favorable environment for establishing most cover crop species, most notably sunflowers which contributed a large percent of the total herbage mass each year (Tables 2.7 and 2.8).

Overall, summer double crops were successfully established in most years and locations throughout the study. An economic analysis is needed to determine whether these double crop yields will produce a net return on production, however even some return on investment may make these crops more profitable than a cover crop which does not produce any immediate returns on investment, unless grazing is implemented. While legumes may fix nitrogen, we did not observe any immediate benefit to wheat grain yield as it was no different between the cover crop and summer fallow treatments in 11 out of 12 site-years. Double crops, and in particular grain sorghum, produced as much, or in many cases more, above ground biomass than the multi-species cover crop and therefore is likely to improve soil security as greater herbage mass can enhance soil carbon storage, increase water retention, ground coverage, microbial activity and protect against erosion.

Table 2.6. ANOVA summary of significance tillage for grain yield and herbage mass of summer double crops cowpea, cover crop, sesame, and grain sorghum at Beeville, Lubbock, and Thrall in Texas from 2016 – 2019.

Effect	Cover crop (kg ha^{-1})				Cowpea (kg ha^{-1})				Sesame (kg ha^{-1})				Sorghum (kg ha^{-1})			
	2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019
Summer double crop grain yield																
Beeville																
Tillage	-	-	-	-	NS	NS	-	NS	*	*	NS	NS	-	NS	NS	NS
SEM	-	-	-	-	30	191	-	123	111	62	66	380	-	762	591	1064
n	-	-	-	-	8	9	-	9	9	9	9	9	-	9	9	8
Lubbock																
Tillage	-	-	-	-	NS	NS	-	NS	NS	-	NS	NS	NS	NS	NS	NS
SEM	-	-	-	-	105	250	-	222	117	-	96	104	1031	588	602	212
n	-	-	-	-	9	9	-	9	8	-	8	9	8	9	9	9
Thrall																
Tillage	-	-	-	-	NS	**	-	NS	NS	NS	NS	*	NS	NS	NS	**
SEM	-	-	-	-	35	59	-	62	228	250	167	168	548	258	251	1093
n	-	-	-	-	9	9	-	9	9	9	9	9	7	9	9	9
Summer double crop herbage mass																
Beeville																
Tillage	NS	NS	NS	NS	NS	NS	NS	NS	-	*	*	NS	-	**	NS	**
SEM	973	1103	782	486	588	276	423	534	-	177	345	221	-	821	1041	821
n	9	9	9	9	9	9	9	9	-	9	9	9	-	9	9	9
Lubbock																
Tillage	*	NS	NS	NS	NS	NS	NS	NS	NS	-	*	NS	NS	NS	NS	NS
SEM	808	1123	1618	640	44	420	297	255	262	-	231	155	325	1424	557	425
n	8	8	8	8	9	9	9	9	9	-	8	9	9	9	9	9
Thrall																
Tillage	NS	NS	*	NS	NS	NS	NS	NS	NS	**	NS	*	NS	NS	NS	*
SEM	422	1472	615	198	90	140	357	460	342	458	331	120	933	620	288	459
n	9	9	9	9	9	9	9	9	9	9	9	9	7	9	9	9

*, **, Significant at the 0.05, and 0.01 probability levels, respectively; [a]NS, not significant; SEM, standard error of mean; n, number of observations used.

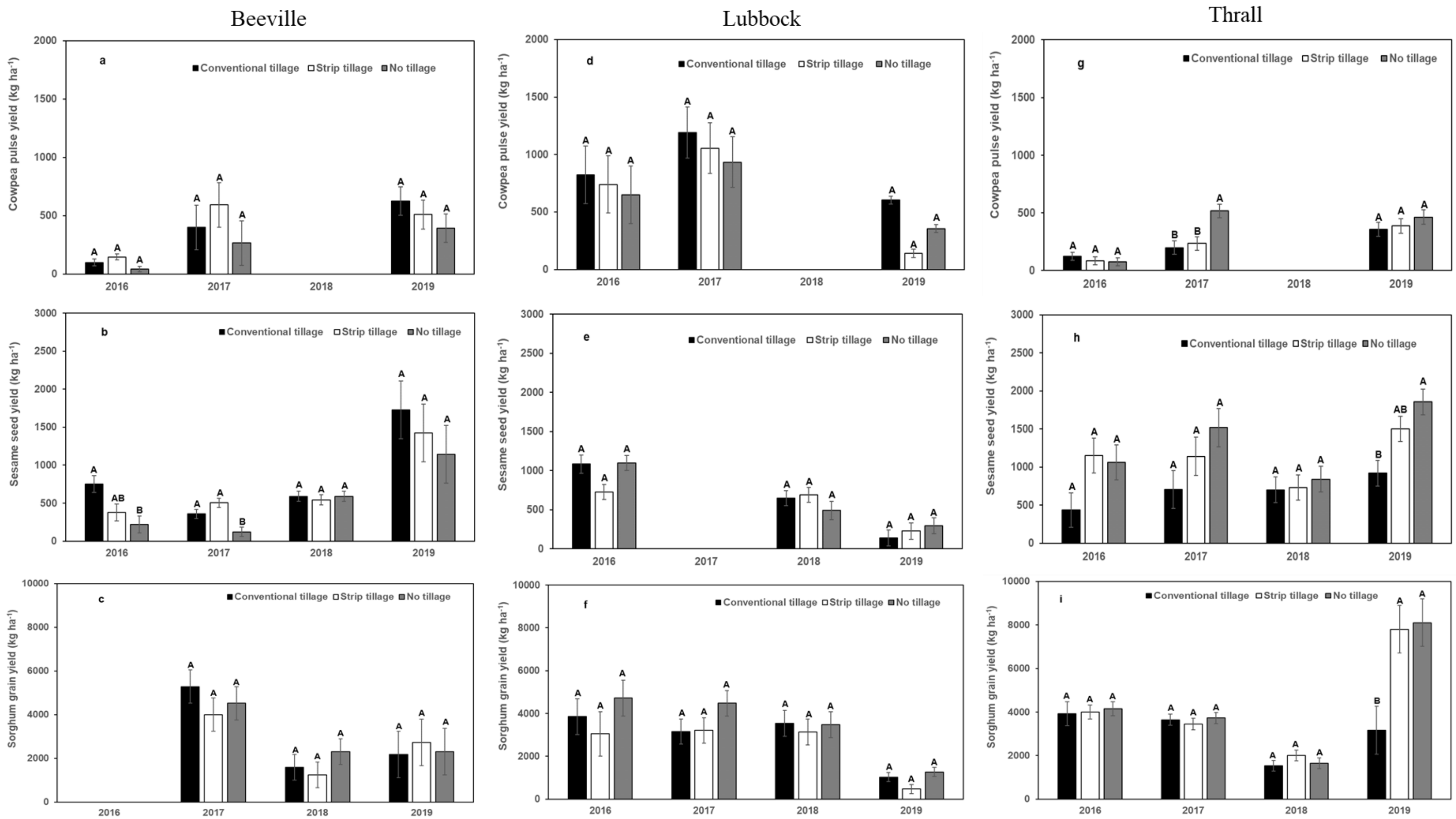

Figure 2.4. Cowpea pulse (kg ha^{-1}), sesame seed (kg ha^{-1}), and sorghum grain yield (kg ha^{-1}) as affected by tillage at Beeville, Lubbock, and Thrall locations in Texas from 2016 – 2019. Bars represent standard error of mean, and different letters within each year at each location are significant (P < 0.05).

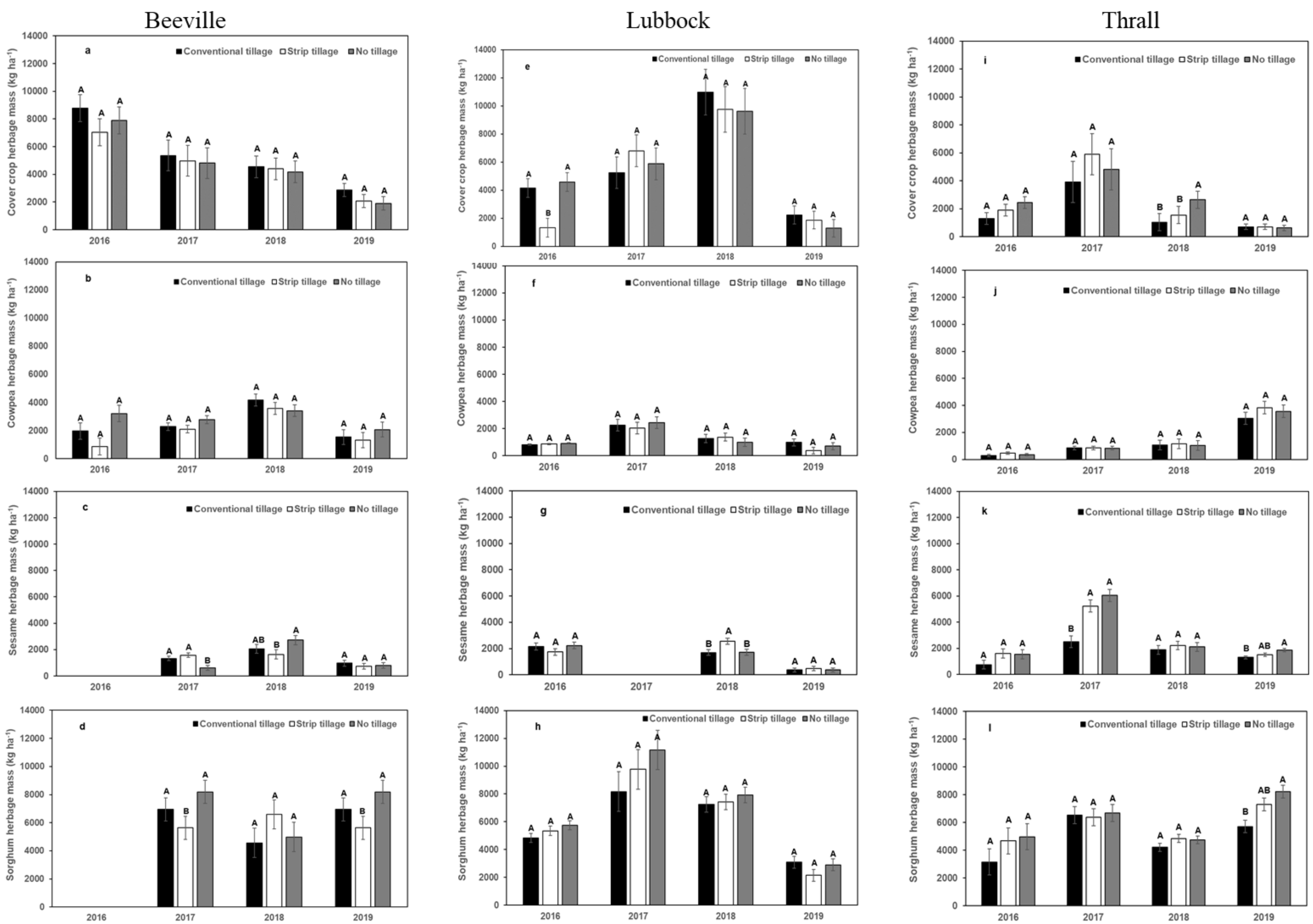

Figure 2.5. Cover crop, cowpea, sesame, and sorghum herbage mass yield (kg ha^{-1}) as affected by tillage at Beeville, Lubbock, and Thrall locations in Texas from 2016 – 2019. Bars represent standard error of mean, and different letters in individual crop within each year at each location are significant (P < 0.05).

Table 2.7. Cover crops species stand count as impacted by year and location in Texas.

Cover crop species stand count (plants m^{-2})										
Location	Year	Buckwheat	Cowpea	Foxtail millet	Guar	Lablab	Peanut	Pearl millet	Sunflower	Sunn hemp
Beeville	2016	0	1	0	0	0	0	4	0	0
	2017	0	3	0	0	0	1	8	0	0
	2018	3	3	-	2	3	-	8	0	1
	2019	0	1	-	3	0	-	11	0	1
Lubbock	2016	2	5	0	2	0	1	4	0	2
	2017	9	4	0	1	0	0	12	1	5
	2018	6	2	-	2	1	-	13	1	2
	2019	-	-	-	-	-	-	-	-	-
Thrall	2016	0	1	0	1	0	0	1	0	0
	2017	4	11	0	3	1	4	26	0	1
	2018	3	4	-	2	0	-	8	2	2
	2019	0	5	-	0	4	-	3	2	0

Table 2.8. Cover crop species herbage mass as impacted by year and location in Texas.

Cover crop species herbage mass yield (kg ha^{-1})										
Location	Year	Buckwheat	Cowpea	Foxtail millet	Guar	Lablab	Peanut	Pearl millet	Sunflower	Sunn hemp
Beeville	2016	-	-	-	-	-	-	-	-	-
	2017	-	-	-	-	-	-	-	-	-
	2018	0	1452	-	162	679	-	4109	0	293
	2019	0	0	-	0	0	-	1979	0	0
Lubbock	2016	43	342	0	137	8	6	1731	405	5
	2017	99	780	0	11	75	0	2475	2246	627
	2018	0	523	-	409	0	-	3867	527	243
	2019	141	112	-	20	0	-	811	1535	0
Thrall	2016	0	475	0	0	165	82	1125	0	44

Table 2.8. Continued

	2017	0.5	438	0	5	74	63	652	0	0
	2018	10	737	-	81	639	-	986	726	507
	2019	0	261	-	0	225	-	222	99	3

2.4. Conclusions and Implications

After four years, reduced tillage systems (NT and ST) and summer double cropping may be achievable in the Coastal Plains and Blackland Prairie ecoregions. Both tillage and summer double cropping treatment impacts on wheat stand establishment, wheat grain yield, and wheat herbage mass were inconsistent across years in all the three ecoregions. There are various perceived reasons given by growers that no tillage does not work consistently across Texas ecoregions, often related to compaction, difficulty planting into hard soils when dry, or difficulty accessing fields to plant due to wetter soils in the fall and spring resulting in delayed planting or poorer stands and yields. In the absence of irrigation at Thrall, reduced tillage improved double yield for years when precipitation events were more sparse. With the proper planting equipment, double crop seed was successfully placed at the desired 2.5-5.0 cm depth and was often placed into moisture when no tilled. Tilling between wheat harvest and double crop planting generally left a rough seedbed and loss of moisture in the seed zone resulting in lower stands and ultimately lower yields in some cases. The NT advantage was not apparent at Lubbock and Beeville where supplemental irrigation was available to offset the subtle differences in seed zone moisture.

Documenting weed control issues was beyond the scope of the trial, but intensifying cropping systems does limit herbicide options available for use without impacting subsequent crops and should be considered. Anecdotal observations indicated that the CT treatment helped control rescuegrass populations in wheat at the Thrall site.

Double cropping in the High Plains region of Texas should be carefully considered based on environment and access to irrigation. While double cropping did not decrease wheat grain yield in any year, the shorter growing season requires a very quick turnaround between harvest of one crop and planting of the subsequent crop. As noted in 2019, a late wheat harvest delayed double crop planting and sorghum and sesame yields were affected by an early killing frost before reaching full maturity. Irrigation would be essential in most cases to ensure rapid emergence as well. Double crop species and/or cultivars that have short growing cycles should be considered at Lubbock to ensure timely maturation before wheat planting; however, limited growing degree days are not a concern at the southern locations at Thrall and Beeville.

Based on the stand count and herbage mass of the multi-species cover crop, pearl millet and cowpea performed better than the rest of the species at Beeville and Thrall; however, the combination of pearl millet, cowpea, sunflower, guar, lablab, sunn hemp, and buckwheat is feasible in Lubbock. Summer double cropping (grain sorghum and sesame) have the potential to improve farmers’ annual net return over cover crop as well as enhance soil health and long-term productivity and sustainability goals.

2.5. References

Adekalu, K.O., and D.A. Okunade. 2006. Effect of irrigation amount and tillage system on yield and water use efficiency of cowpea. Communication in Soil Science and Plant Analysis. 37:1–2, 225–237. doi:10.1080/00103620500403465.

Ahmad Khan, M.T. Jan, M. Arif, K.B. Marwat, and A. Jan. 2008. Phenology and crop stand of wheat as affected by nitrogen sources and tillage systems. Pak. J. Bot., 40:1103–1112.

Aikins, S.H.M., and J.J. Afuakwa. 2010. Effect of four different tillage practices on cowpea performance. World J. Agric. Sci., 6:644–651. ISSN 1817-3047.

Akinyemi, J.O., O.E. Akinpelu, and A.O. Olaleye. 2003. Performance of cowpea under three tillage systems on an oxic paleustalf in southwestern Nigeria. Soil Tillage Res. 72:75–83. doi:10.1016/S0167-1987(03)00066-7.

Alexandratos, N., and J. Bruinsma. 2012. World agriculture towards 2030/2050. Land use policy 20:375.

Alvarez, R., and H.S. Steinbach. 2009. A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crop yield in the Argentine Pampas. Soil Tillage Res. 104:1–15. DOI: 10.1016/j.still.2009.02.005.

Anken, T., P. Weisskopf, U. Zihlmann, F. Hans-Rudolf, J. Jansa, and K. Perhacova. 2004. Long-term tillage system effects under moist cool conditions in Switzerland. Soil Till. Res. 78. 171–183. 10.1016/j.still.2004.02.005.

Baumhardt, R.L., Zartman, R.E., and Unger, P.W., 1985. Grain sorghum response to tillage method used during fallow and to limited irrigation. Agron. J. 77:643–646.

Borchers, A., E. Truex-Powell, S. Wallander, and C. Nickerson. 2014. Multi-cropping practices: recent trends in double cropping, EIB-125. U.S. Department of Agriculture, Economic Research Service, May 2014.

De Vita, P., E. Di Paolo, G. Fecondo, N. Di Fonzo, M. Pisante. 2007. No-tillage and conventional tillage effects on durum wheat yield, grain quality and soil moisture content in southern Italy. Soil Tillage Res. 92:69–78. doi:10.1016/j.still.2006.01.012.

Derpsch, R., A.J. Franzluebbers, S.W. Duiker, D.C. Reicosky, K. Koeller, T. Friedrich, W.G. Sturny, J.C.M. Sa, and K. Weiss. 2014. Why do we need to standardize no-tillage research? Soil Till. Res. 137:16–22. doi:10.1016/j.still.2013.10.002.

Dobberstein, J. 2014. U.S. No-Tilled Acres Reach 96 Million. No-till Farmer. Poster. https://www.no-tillfarmer.com/articles/2512-us-no-tilled-acres-reach-96-million (accessed 2 Nov. 2019).

Doran, J.W., and M.R. Zeiss. 2000. Soil health and sustainability: Managing the biotic component of soil quality. Appl. Soil Ecol. 15:3–11. doi:10.1016/S0929-1393(00)00067-6.

Erenstein, O., K. Sayre, P. Wall, J. Hellin, and J. Dixon. 2012. Conservation agriculture in maize- and wheat-based systems in the (sub)tropics: lessons from adaptation initiatives in South Asia, Mexico, and Southern Africa. J. Sustain. Agric. 36:180–206. doi:10.1080/10440046.2011.620230.

FAO. 2011. FAO Statistics. Food Agric. Organ. United Nations. http://faostat3.fao.org/home/E%5Cnhttp://faostat3.fao.org/faostat-gateway/go/to/download/Q/QC/E%5Cnhttp://faostat3.fao.org/ (accessed 8 Feb. 2019).

Farooq, M., K.C. Flower, K. Jabran, A. Wahid, and K.H.M. Siddique. 2011. Crop yield and weed management in conservation agriculture. Field Crops Res. 117:172–183. doi:10.1016/j.still.2011.10.001.

Farvid, M.S., E. Cho, A.H. Eliassen, W.Y. Chen, and W.C. Willett. 2016. Lifetime grain consumption and breast cancer risk. Breast Cancer Res. Treat. 159:335–345. doi:10.1007/s10549-016-3910-0.

Foley, J., N. Ramankutty, K. Brauman et al. 2011. Solutions for a cultivated planet. Nature, 478:337–342. doi:10.1038/nature10452.

Flynn, R., 2015. Inoculation of Legumes. NMSU Coop Ext. Guide A-130. http://aces.nmsu.edu/pubs/_a/A130.pdf (accessed March 2019).

Foster, J.L., M.E. Bean, C. Morgan, G. Morgan, R. Mohtar, J. Landivar, and M. Young. 2018. Comparison of two tillage practices in a semi-arid cotton-grain sorghum rotation. Agron. J. 110:1572–1579. doi:10.2134/agronj2017.12.0706.

Franzluebbers, A.J., F.M. Hons, and V.A. Saladino. 1995. Sorghum, wheat and soybean production as affected by long-term tillage, crop sequence and N fertilization. Plant Soil 173:55–65.

Hajabbasi, M.A. 2003. Effects of different tillage practices on physical properties of a clay-loam soil in northwest of Iran. In: Proceedings of the 16th Conference of the International Soil Tillage Research Organization, Brisbane, Australia. 519–523.

Hay, R.K.M., J.C. Holmes, E.A. Hunter. 1978. The effects of tillage, direct drilling and nitrogen fertiliser on soil temperature under a barley crop. J. Soil Sci., 29:174–183. doi: 10.1111/j.1365-2389.1978.tb02048.x.

Hemmat, A., and I. Eskandari. 2006. Dryland winter wheat response to conservation tillage in a continuous cropping system in northwestern Iran. Soil Tillage Res. 86:99–109. doi:10.1016/j.still.2005.02.003.

Ibrahim, A.M.H., Rudd, J., Devkota, R., Baker, J., Sutton, R., Simoneaux, B., Opeña, G., Herrington, R., Rooney, L., Dykes, L., Awika, J., Nelson, L.R., Fritz, A., Bowden, R.L., Graybosch, R.A., Jin, Y., Seabourn, B.W., Chen, X., Kolmer, J., Amand, P. St., Bai, G., and Duncan, R.. 2015. Registration of ‘TAM 305’ hard red winter wheat. J. Plant Reg. 9:325–330. doi:10.3198/jpr2014.08.0054crc.

Izaurralde, R.C., J.A. Hobbs, and C.W. Swallow. 1986. Effects of reduced tillage practices on continuous wheat production and on soil properties.

Keeling, W., E. Segerra, and J.R. Abernathy. 1989. Evaluation of conservation tillage cropping systems for cotton on the Texas High Plains. J. Prod. Agric. 2:269–273. doi:10.2134/jpa1989.0269.

Kibblewhite, M.G., K. Ritz, and M.J. Swift. 2008. Soil health in agricultural systems. Phil. Trans. R. Soc. B. 363:685–701 doi:10.1098/rstb.2007.2178.

Lal, R. 2001. Soil degradation by erosion. Land Deg. Dev. 12: 519–539. doi:10.1002/ldr.472.

Langham D.R., J. Riney, G. Smith, T. Wiemers, D. Pepper, and T. Speed. 2010. Sesame Producers Guide. Sesaco Corp.

Lithourgidis, A.S., K.V. Dhima, C.A. Damalas, I.B. Vasilakoglou, and I.G. Eleftherohorinos. 2006. Tillage Effects on Wheat Emergence and Yield at Varying Seeding Rates, and on Labor and Fuel Consumption. Crop Sci. 46:1187–1192. doi:10.2135/cropsci2005.09-0321

Lithourgidis, A.S., C.A. Tsatsarelis, and K.V. Dhima. 2005. Tillage effects on corn emergence, silage yield, and labor fuel inputs in double cropping wheat. Crop Sci. 45:2523–2528. doi:10.2135/cropsci2005.0141.

Magdoff, F., and H. Van Es. 1993. Building Soils for Better Crops Sustainable Soil Management. Third Edition. http://faculty.washington.edu/elizaw/building%20Soils%20for%20better%20crops.pdf (accessed 11 Sept. 2019).

Marburger, D.A., A. Silva, R.M. Hunger, J.T. Edwards, L.V. Laan, A.M. Blakey, C-C. Kan, K.A. Garland-Campbell, R.L. Bowden, L. Yan, M. Tilley, M-S. Chen, Y.R. Chen, G. Bai, Y. Jin, J.A. Kolmer, B.W. Seabourn, G.D. Rassi, P. Rayas-Duarte, R.M. Ker, and B.F. Carver. 2021. ‘Gallagher’ and ‘Iba’ hard red winter wheat: Half-sibs inseparable by yield gain, separable by producer preference. J. Plant Reg. 15:177–195. doi:10.1002/plr2.20116.

Massee, T.W., and J.W. Cary. 1978. Potential for reducing evaporation from summer fallow. J. Soil Water Conserv. 33:126–129. https://eprints.nwisrl.ars.usda.gov/337/1/403.pdf (accessed 6 July 2020).

Matsi, T., A.S. Lithourgidis, and A.A. Gagianas. 2003. Effects of injected liquid cattle manure on growth and yield of winter wheat and soils characteristics. Agron. J. 95:592–596.

Mrabet, R. 2000. Differential response of wheat to tillage management systems in a semiarid area of Morocco. Field Crop Res. 66:165–174. PII: S0378-4290(00)00074-5.

National Oceanic and Atmospheric Administration (NOAA). 2020. https://www.noaa.gov/ (accessed 4 July. 2020).

Norwood, C.A., A.J. Schlegel, D.W. Morishita, and R.E. Gwin. 2013. Cropping system and tillage effects on available soil water and yield of grain sorghum and winter wheat. J. Prod. Agric. 3:356–362.

Riley, H., T. Børrensen, E. Ekeberg, T. Rydberg. 1994. Trends in reduced tillage research and practice in Scandinavia. M.R. Carter (Ed.), Conservation Tillage in Temperate Agroecosystems, Lewis Publishers, Boca Raton, Florida, USA. 23–45.

Rothrock, C.S. 1987. Take-all of wheat as affected by tillage and wheat-soybean double cropping. Soil Bio. Biochem. 19:307–311.

Rudd, J.C., R.N. Devkota, A.M. Ibrahim, J.A. Baker, S. Baker, R. Sutton, B. Simoneaux, G. Opena, D. Hathcoat, J.M. Awika, L.R. Nelson, S. Liu, Q. Xue, B. Bean, C.B. Neely, R.W. Duncan, B.W. Seabourn, R.L. Bowden, Y. Jin, M-S. Chen, R.A. Graybosch. 2019. 'TAM 204' Wheat, adopted to grazing, grain, and graze-out production systems in the Southern High Plains. J. Plant Reg. 13:377–382. doi:10.3198/jpr2018.12.0080crc.

Rudd, J.C., R.N. Devkota, A.M. Ibrahim, D. Marshall, R. Sutton, J.A. Baker, G.L. Peterson, R. Herrington, L.W. Rooney, L.R. Nelson, G.D. Morgan, A.K. Fritz, C.A. Erickson, and B.W. Seabourn. 2015. 'TAM 304' wheat, adapted to the adequate rainfall or high-input irrigated production system in the southern Great Plains. J. Plant Reg. 9:331–337. doi:10.3198/jpr2015.02.0004crc.

Rusinamhodzi, L., M. Corbeels, M. van Wijk, M.C. Rufinio, J. Nyamangara, K.E. Giller. 2011. A meta-analysis of long-term effects of conservation agriculture practices on maize yields under rain-fed conditions. Agron. Sustain. Dev. 31:657–673. doi:10.1007/s13593-011-0040-2.

SAS Institute. 2010. SAS/STAT 9.22 user's guide. Cary, NC: SAS Institute.

Schillinger, W.F. 2001. Minimum and delayed conservation tillage for wheat-fallow farming. Soil Sci. Soc. Am. J. 65:1203–1209.

Shaver, T.M., G.A. Peterson, L.R. Ahuja, D.G. Westfall, L.A. Sherrod, and G. Dunn. 2002. Surface Soil Physical Properties After Twelve Years of Dryland No-Till Management. Soil Sci. Soc. Am. J. 66:1296.

Sheahan, C.M. 2014. Plant guide for sesame (Sesamum orientale). USDA-Natural Resources Conservation Service, Cape May Plant Materials Center, Cape May, NJ.

Slavin, J. 2004. Whole grains and human health. Nutr. Res. Rev. 17:99–110. doi:10.1079/NRR200374.

Soane, B.D., B.C. Ball, J.A. Arvidsson, G. Basch, and J. Roger-Estrade. 2012. No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. Soil and Tillage Res. 188:66–87. doi:10.1016/j.still.2011.10.015.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at the following link: http://websoilsurvey.sc.egov.usda.gov/. (accessed 16 March 2021).

Sow, A.A., L.R. Hossner, P.W. Unger, and B.A. Stewart. 1997. Tillage and residue effects on root growth and yields of grain sorghum following wheat. Soil Tillage Res. 44:121–129. PII S0167-1987(97)00042-1.

Tebrugge, F., and R.A. During. 1999. Reduced tillage intensity – a review of results from a long-term study in Germany. Soil & Tillage Research 53:15–28. doi:10.1016/S0167-1987(99)00073-2.

USDA-NASS, 2020. Small Grains 2020 Summary. ISSN: 1949-162X. https://downloads.usda.library.cornell.edu/usda-esmis/files/5t34sj573/7p88d6171/bn999x131/smgr0920.pdf (accessed 30 October 2020).

Van Ouwerkerk, C., and U.D. Perdok. 1994. Experiences with minimum and no-tillage practices in the Netherlands. I: 1962-1971. F. Tebrügge, A. Böhrnsen (Eds.), Experience with the Applicability of No-tillage Crop Production in the West-European Countries. Proc. EC-Workshop-I, Wissenschaftlicher Fachverlag, 35428 Langgöns, Germany. 59–67.

Wilkins, D.E., B. Klepper, and R.W. Rickman. 1989. Measuring wheat seedling response to tillage and seeding systems. Trans. ASAE 32:795–800.

CHAPTER III

CAN DOUBLE CROPPING AND NO-TILL SYSTEMS IMPACT SOIL PHYSICAL PROPERTIES IN WHEAT PRODUCTION SYSTEMS IN TEXAS?

3.1. Introduction

Intensive use of heavy equipment, conventional tillage (CT), and fallow periods are examples of agricultural practices that contribute to increased soil degradation (Foley et al., 2011; Hobbs et al., 2007; Holland, 2004; Hussain et al., 1998). Degradation of agricultural soil due to erosion, loss of organic carbon (OC), contamination, compaction, increased salinity, or decrease of ecosystem services, such as C sequestration or nutrient cycling, are evidence of poor soil management practices (European Commission, 2002; Kibblewhite et al., 2008). Information about tillage, crop rotations, and water and soil management practices that improve soil health and function are key to long-term sustainability and productivity of agricultural ecosystems. A key soil function in Texas is capturing and storing precipitation for crop production due to high evaporative demands and intense rainfall events (Massee and Cary, 1978; Dhuyvetter et al., 1996; Unger et al., 1984). This study seeks to quantify the impact of soil health promoting practices, including conservation tillage and increasing soil cover, on hydrologically important soil physical properties.

Soil tillage is a key management practice that drives changes in soil physical properties (Tebrugge and During, 1999; Lal, 2001; Pittelkow et al., 2014). No tillage (NT) is a conservation tillage management practice that preserves soil security by reducing soil erosion (Lal, 2001), and increasing soil OC content and aggregate stability (Alvarez and Steinbach, 2009) and biological activity (Anken et al., 2004). No tillage can promote increased soil OC through slower decomposition of crop residues to support and improve soil function (Tebrugge and During, 1999). No tillage can also reduce labor costs, enhance soil quality, and help in soil and water conservation (DeLaune and Sij, 2012; Foster et al., 2018).

Several studies have suggested residues or ground coverage on the soil's surface create a physical barrier resulting in less water evaporation and reduced erosion, as well as increased OC, aggregate stability, infiltration, and ultimately soil security (Blanco-Canqui et al., 2013; Massee and Cary, 1978; Tebrugge and During, 1999). Massee and Cary (1978) reported that less than 30% of precipitation was stored during the summer fallow period and suggested that water loss may be due to the exposure of the soil surface to wind and solar energies that facilitate evaporation coupled with erosion. Diverse crop rotations, such as cover crops or double cropping, can maximize beneficial effects of reduced tillage for erosion control through soil surface cover (Keeling et al., 1989).

The combination of double cropping in a wheat (*Triticum* sp.)-sorghum [*Sorghum bicolor* (L.) Moench]-sunflower [*Helianthus annuus* L.] rotation, or combining cover crops and NT increased soil moisture conservation, productivity, and net returns in the Great Plains (Dhuyvetter et al., 1996; Unger et al., 1984). While continuous cropping and CT can lead to soil degradation over time, which may decrease long-term sustainability and economic viability (Alexandratos and Bruinsma, 2012; Tebrugge and During, 1999). Soil security and soil health can be improved through crop residue retention, diverse cropping systems, and conservation tillage systems such as NT (Kahlon et al., 2013; Pittelkow et al., 2014). What is less clear is the relative contributions of conservation tillage and diverse crop rotations on any potential improvements in soil physical properties and overall soil health.

Texas is one of the largest wheat producing states in the U.S., and in 2020, 17.9 million hectares were planted in the U.S. and 1.98 million hectares planted in Texas (USDA-NASS, 2020). Wheat production in Texas is dominated by CT and summer fallow, exposing the soil to erosion and water loss through evaporation (Massee and Cary, 1978). Including summer-planted double crops, such as grain sorghum, during the typical summer fallow is an opportunity to diversify and intensify wheat cropping systems. Integration of both NT and summer double crops in annual wheat production systems may improve productivity and soil properties such as OC, aggregate stability, infiltration, biological activities, water holding capacity, and reduce erosion (Alexandratos and Bruinsma, 2012; Alvarez and Steinbach, 2009; Holman et al., 2020; Tebrugge and During, 1999). In Texas, only 2.1% of agricultural lands are used for double cropping (Borchers et al., 2014), and only 8.8% of agricultural lands in Texas are managed with NT farming practices (Dobberstein, 2014), ranking Texas among the lowest states in the U.S. in terms of NT implementation.

We hypothesize that reducing tillage intensity and increasing cropping systems diversity will improve infiltration rate, wet aggregate stability, soil moisture content, and reduce runoff rate. Thus, the objectives of this study were to quantify the effects of reduced tillage and summer double cropping systems on soil physical properties assessed through infiltration, runoff, time-to-runoff, wet aggregate stability (WAS), and soil moisture content over time in three agriculturally important ecoregions in Texas: Coastal Plains, South High Plains, and Blackland Prairie.

3.2. Materials and Methods

3.2.1. Experimental Sites and Weather Data

The experiment was conducted for five years (fall of 2015 to summer of 2020) in three locations (Beeville, Lubbock, and Thrall, TX). These three locations represented three important agricultural ecoregions in Texas. The Beeville site was located at the Texas A&M AgriLife Research Station (28° 27'N 97° 42'W; 74 m elevation) in the Coastal Plains ecoregion. The Beeville soil was classified as a Parrita sandy clay loam (loamy, mixed, superactive, hyperthermic, shallow Petrocalcic Paleustoll) (Soil Survey Staff, 2021). The Lubbock site was located at the Texas A&M AgriLife Research and Extension Center (33° 41'N 101° 49'W; 1001 m elevation) in the High Plains ecoregion. The Lubbock soil was classified as an Olton clay loam (fine, mixed, superactive, thermic Aridic Paleustolls) (Soil Survey Staff, 2021). The Thrall site was located at the Stiles Farm Foundation (30° 36'N 97° 18'W; 173 m elevation) in the Blackland Prairies ecoregion, and the soil was classified as a Burleson clay (fine, smectitic, thermic Udic Haplusterts) (Soil Survey Staff, 2021). The land use history in the three locations prior to this trial were perennial peanut (*Arachis glabrata* Benth.) for 25 years at Beeville, Thrall site was planted with cotton (*Gossypium hirsutum* L.) for over 10 years (CT), and the Lubbock site was CT cotton for more than 10 years. Data for monthly rainfall, and average monthly temperature data were collected through the National Oceanic and Atmospheric Administration (NOAA, 2020) and are shown in Figure 2.1 (Chapter 2). Beeville site weather data was collected from the Beeville 5 NE, TX US station within 1.2 km from the experimental site. Lubbock weather data was collected from Lubbock Preston Smith International Airport Station, TX US within 1.9 km from the site. Thrall weather data was collected from Thrall 10.5 SSE, TX US station within 24.1 km from the site. Soil characteristics of all three locations are reported in Table 2.1 (Chapter 2).

3. 2.2. Treatments and Experimental Design

The experimental design was a randomized complete block split-plot design with three replications at all three locations. Treatments were randomly assigned to experimental units in

2015, and the same treatments were imposed each year. The main plots were the three tillage treatments (CT, NT, and ST), and the subplots were the five summer double crop treatments which included a cover crop mixture, cowpea [*Vigna unguiculata* (L.) Walp], grain sorghum, sesame [*Sesame indicum* L.], and summer fallow control. The experimental unit size at Beeville was 9.1 m long by 3.0 m wide, Lubbock was 12.2 m long by 4.1 m wide, and Thrall was 22.9 m by 7.6 m wide.

3.2.3. Cropping System Management

At Beeville and Thrall locations, CT plots were tilled at 15-cm depth using a disk Case IH 370 (Racine, WI, USA). Strip till plots were tilled at 15-cm depth with an Orthman 1tRIPr (Lexington, NE, USA) with individual disk spacing of 76 cm. At Beeville, a modified 1.5-m Great Plains NT drill was used to plant wheat. At Thrall, a modified 1.5-m Great Plains NT drill (2015-2016, and 2019-2020) while a 3.7-m JD 8200 and Sunflower 9.1-m NT drill 9421 were used to plant wheat in 2017 and 2018, respectively. Summer double crops were planted at Beeville and Thrall with a 2-row John Deere Max Emerge Plus planter unit fitted with Almaco 31-cell cones for seed metering. Conventional tillage received three passes, while ST received a single pass at both Beeville and Thrall. At Lubbock, CT plots were tilled with John Deere tandem disk, model 630 with a 4.3 m width that ran 15 cm deep. Prior to putting up beds in the CT plots, they were disked twice, once from each direction. For ST plots, the implement was an Orthman 1tRIPr that is 4 rows (1.16 m) wide. Each individual strip was 30 cm wide and ran 7.5 cm deep. The drill used for wheat planting was a Great Plains minimum till drill, model 1200, with a 3.7 m width. The planter used for summer double crops was a John Deere Max Emerge Plus 1700 that is 4-rows wide with Almaco 31-cell cones.

Wheat varieties for each location were selected based on their adaptability across regions and over the course of the study needed to be changed to address yield limiting issues such as poor vernalization at Beeville and Thrall, weed control at Thrall, and wheat streak mosaic virus at Lubbock. In Beeville, hard red winter wheat cultivar 'TAM 304' (Rudd et al., 2015) was planted in year one and was changed to hard red winter wheat cultivar 'TAM 305' (Ibrahim et al., 2015) in year two, and hard red spring wheat cultivar 'LCS Trigger' (Limagrain, Saint-Beauzire, Puy-de-Dôme, France) was planted for the final three seasons of the study. In Lubbock, 'TAM 304' was planted in the first two years of the study and was changed to hard red winter wheat cultivar 'TAM 204' (Rudd et al., 2019) in years three through five, though overall poor stands in year four required a replant using the spring wheat variety 'LCS Trigger'. In Thrall, hard red winter wheat cultivar 'WB Cedar' (Westbred, Fargo, ND, USA) was planted in the first two years, changed to hard red winter wheat cultivar 'Gallagher' (Marburger et al., 2021) in year three because of poor vernalization by WB Cedar, and LCS Trigger in year four and five to allow for later planting and better fall weed control. The row spacing for wheat planting was 19-cm for all three locations. In the ST treatment, the wheat crop was planted using NT, as tilled strips were wider than the row spacing for wheat. Planting the spring wheat LCS Trigger allowed for later planting and better fall weed control because of encroaching rescuegrass populations. The row spacing for wheat planting was 19-cm for all three locations. In the ST treatment, the wheat crop was planted using NT, but subsequent summer crop planted by ST.

The summer double crops were planted on a row spacing of 76 cm in Beeville and Thrall, and 102 cm row spacing for Lubbock in order to follow the typical row spacing practices in each ecoregion. The cover crop mixture consisted of buckwheat ['Mancan', *Fagopyrum* *esculentum* Moench], cowpea 'Iron and Clay' [*Vigna unguiculata* (L.) Walp], guar ['Kinman', *Cyamopsis tetragonoloba* (L.) Taubert], lablab ['Rio Verde', *Lablab purpureus* (L.) Sweet], short stature sunflower ['8H668S', *Helianthus annuus* L.], pearl millet [*Pennisetum glaucum* (L.) R. Br.], sunn hemp [*Crotalaria juncea* L.], peanut 'Tamrun OL 11', and German foxtail millet [*Setaria italic* (L.) P. Beauv.]. Annual peanut and German foxtail millet were removed from the cover crop mixture in year three due to peanut incompatibility with the other cover crop species planting depth, and German foxtail millet poor stands.

All summer double crops, except sesame, were pre-treated with Apron XL fungicide (Mefenoxam, Syngenta, Greensboro, NC, USA), Cruiser 5FS insecticide (Thiamethoxam, Syngenta, Greensboro, NC, USA), and Dual safener. The cover crop mixture and the cowpea treatments were treated at the time of planting with a powdered Rhizobium species (N-DURE, Verdesian, Cary, NC, USA) to inoculate seeds (Flynn, 2015). Wheat and summer double crops seeding rates, and planting and harvest dates are detailed in Tables 2.2 and 2.3 in Chapter 2. Wheat fertilization was based on summer soil sample results and recommendations from the Texas A&M AgriLife Extension Service Soil, Water, and Forage Testing Laboratory (College Station, TX), and double crop fertilization based on winter soil sampling (Chapter 2, Table 2.4). To avoid bird damage, wire mesh crop cages (1.5 m × 1.2 m) were installed across two center rows in each sorghum plot at all three locations.

3.2.4. Response Variables

3.2.4.1. Infiltration, Time-to-Runoff, Runoff, and Sorptivity

Two infiltration methods were used for this study: single ring infiltration (USDA-NRCS, 2001) and Cornell sprinkle infiltration (van Es and Schindelbeck, 2003). The single ring infiltration method was used for the CT and NT treatments of all five summer double crop treatments at each research location. This was performed immediately following wheat harvest and before summer crop planting by taking three replicated measurements in each experimental unit and avoiding tractor tire tracks, cracks, ant mounds, and heavy debris. The single ring infiltration measurements were taken for two years (2018 and 2020) at Beeville, while at both Lubbock and Thrall, infiltration measurements were taken for three years (2017, 2018, and 2020). Measurements were taken within a two-day span at each location to ensure continuity of soil moisture using the NRCS method (USDA-NRCS, 2001). A 24.1 cm metal ring was pounded into the soil to a 7 cm depth and leveled. Then, the first infiltration reading was taken by pouring 2.54 cm water uniformly into the ring and timed from the moment the water came into contact with the soil surface until all water within the ring infiltrated into the soil. After recording the first infiltration reading time, a second 2.54 cm of water was poured into the ring and timed. The measurement was stopped after one hour if the water did not infiltrate and the height of any remaining water measured.

Steady state infiltration rate, time-to-runoff, sorptivity, and runoff measurements were measured using Cornell sprinkle infiltrometers (Ithaca, NY) at the same time as the single ring measurements (Diskin and Nazimoz, 1996; van Es and Schindelbeck, 2003). The measurements were taken in fallow, grain sorghum, and cover crop treatments in CT and NT plots at three locations per plot for three consecutive years at Beeville (2018 to 2020), and four consecutive years at Lubbock and Thrall (2017 to 2020). A portable rainfall simulator (calibrated and set to 30 cm hr^{-1}) was placed on a single 24.1 cm diameter infiltration ring and installed at a 7 cm depth. Runoff was collected and the height of the water in the chamber recorded approximately every four to six min, depending on the rate of infiltration, from time of runoff, measuring the total input and output of water during that time interval and was performed for approximately 45 minutes. If the measurement entered a second day, water that was degassed the previous night was poured into the infiltrometer to the 40 cm mark. Runoff rate (ro_t) was calculated by:

$$rt_o = \frac{V_t}{457.3 * t}$$

Equation 1

Where 457.3 cm^2 was the area of the infiltrometer ring, t was the time interval for taking the volume of runoff water at time t (V_t). Infiltration rate was calculated by the difference between the simulated rainfall rate and runoff rate when it reached the steady-state conditions (van Es and Schindelbeck, 2003). Steady state infiltration rate was estimated by fitting a power function to the data and then standardizing the time to 45 minutes.

Sorptivity (S) was used to estimate the initial infiltration conditions and was calculated by:

$$S = (2 * T_{RO})^{0.5} * r$$

Equation 2

where T_{RO} was the time-to-runoff and r was the rainfall rate.

3.2.4.2. Wet Aggregate Stability

For WAS test, soil samples were collected at each of the locations from the surface soil layer (0-2 cm) after harvesting the wheat and prior to planting the double crops. The WAS samples were collected for two consecutive years at Beeville (2018 to 2019), and three consecutive years (2017 to 2019) at Lubbock and Thrall. Bulk soil samples were collected by using a trowel; a soil surface sample of 10 cm long by 3 cm wide by 2 cm deep was removed and placed carefully into a paper bag. Three samples per experimental unit (plot) were collected and composited. Samples were air-dried. The Cornell sprinkle infiltrometer was used to measure WAS (van Es and Schindelbeck, 2003). Air-dried samples (~30 g) of soil aggregates ranging from 0.25 to 2.0 mm were sieved for the analysis from the bulk soil sample. The soil aggregates were placed on a 20 cm diameter stacked soil sieves, with catch pans underneath. Aggregates were placed 50 cm below the suspended rainfall simulator that delivered a simulated rain even of approximately 11,700 drops, 4 mm in diameter for 5 minutes and allowed a 12.5 mm of water with a velocity of 3.1 m s^{-1}, delivered 1.9 joules/5 minutes. The remaining soil was dried, and weighed. The percent of stable soil aggregates on a mass basis was calculated as the difference between the original weight (total aggregates) and the remaining aggregates (stable aggregates). The 2017 soil samples were sent to Cornell Soil Health Institute, Ithaca, NY for WAS analyses while the 2018 and 2019 soil samples were analyzed in our lab at the department of Soil and Crop Sciences, Texas A&M University.

3.2.4.3. Soil Moisture Content Over Time

In 2016, after the emergence of summer double crops, aluminum access tubes with a diameter of 5.1 cm, and length of 1.8 m were installed near the center of each experimental unit within a planted row. The aluminum access tubes were cut beforehand at 30 cm below the soil surface and a 5.1 cm pipe, 10 cm in length, was used as a collar to connect the two ends. At each tilling and planting event, the tops were removed, and the bottom portion plugged to prevent soil from entering the access tubes. A neutron moisture meter (503 ELITE Hydroprobe, InstroTek, Inc., Research Triangle Park, NC, USA) was used to determine the water content of soil at multiple depths. At Beeville, the depths were 20, 40, 80, 120 cm below the soil surface, while at Lubbock depths were 15, 30, 45, 60, 75, 90, and 105 cm. At Thrall, the depths were 20, 40, 80, 120, and 160 cm below the soil surface. Lubbock and Thrall locations had site-specific calibrations (Evett and Steiner, 1995), while a sand barrel calibration was used at Beeville, and readings used a 30-sec collection time (Beeville and Thrall) and 15-sec collection time (Lubbock).

3.2.5. Statistical Analysis

Data for infiltration measurements, sorptivity, time-to-runoff, runoff, and WAS were analyzed using PROC GLIMMIX in SAS (SAS Institute, 2010). Treatments (tillage and crop) and their interaction were considered fixed effects; whereas, block and block × tillage were considered random effects. Data were analyzed within location since each location represented a different ecoregion. Year was significant for all dependent variables at all locations, so data were analyzed within year and location. The LSMEANS function with the PDIFF option was used to determine mean separation among significant effects or interactions. Soil moisture over time was analyzed using the REPEATED statement with PROC GLM. Significance was declared at $P \leq 0.05$.

3.3. Results and Discussion

3.3.1. Infiltration

There was a tillage × crop interaction at Beeville and Lubbock for single ring infiltration rate (Tables 3.1 and 3.2, Figures 3.1a and c). The tillage × crop interaction occurred at Beeville because NT reduced the infiltration rate for cover crop and sesame compared to CT, but increased infiltration rate for cowpea in 2018. Interestingly, NT then reduced infiltration rate for cowpea (6.6 cm h^{-1}) over CT in 2020. In 2020, sesame improved infiltration rate over the fallow control in CT while sesame and sorghum improved the infiltration rate over fallow in the NT (Figure 3.1a).

The tillage × crop interaction effect at Lubbock for single ring infiltration rate occurred due to inconsistency for tillage and summer double cropping treatment combinations. For instance, in 2018, NT improved infiltration rate for fallow (17.7 cm h^{-1}) but reduced infiltration rate for cowpea, while in 2020 NT reduced infiltration rate for fallow (8.7 cm h^{-1}). When compared to the fallow control cowpea (CT-2018) and cover crop (NT-2020) improved infiltration rate while cowpea (NT-2018; CT-2020) and cover crop (NT-2018) reduced infiltration rate at Lubbock (Figure 3.1c). At Thrall, the NT treatment was numerically lower than CT in all three years, but was only significant in 2017 (Table 3.3, Figure 3.1e).

Steady state infiltration rate measured with Cornell sprinkler infiltrometers at Beeville was not impacted by tillage, crop, and the tillage x crop interaction (Table 3.1, Figure 3.1b). There was a tillage × crop interaction at Lubbock because steady state infiltration rate was lower in NT-sorghum than other NT treatments or CT-sorghum in 2017, while steady state infiltration rate for NT-fallow increased over CT-fallow and infiltration rate also increased for CT-cover crop and CT-sorghum over CT-fallow (Table 3.2, Figure 3.1d). In 2019, steady state infiltration rate for NT-fallow increased over CT-fallow and infiltration rate also increased for CT-cover crop over CT-fallow at Lubbock. At Thrall, main and interaction effects did not affect steady state infiltration in any year other than in 2020 double crop was significant (Table 3.3). Steady state infiltration rate was greater in sorghum (10.2 cm h^{-1}) and fallow (8.1 cm h^{-1}) than cover crop (5.4 cm h^{-1}) in 2020 while no summer double cropping impact was observed in the previous three years at Thrall (Figure 3.1f).

Other studies have reported faster infiltration rates under NT compared to CT, suggesting improved soil structure and soil aggregation in NT systems which over time results in increased infiltration rate (Gathala et al., 2011; Jat et al., 2009; Vogeler et al., 2009). Savabi et al.

(2007) found similar results in NT systems on silty loam and silty clay loam soils. However, infiltration rates in NT systems may not always be greater than CT in the short term, despite greater soil surface residue which can contribute to greater infiltration rates (Soane et al., 2012). Slowly accruing soil benefits such as aggregate stability, soil fertility, soil biological properties, decreasing evaporation, and reducing runoff (Palm et al., 2013) can take years to manifest, especially in NT systems (Kassam et al., 2009). In Lincoln, NE, Blanco-Canqui et al. (2017) reported no differences among NT, disk, and chisel plow systems on infiltration rate in a long-term study (35 yrs.) and suggested that compressed soil surface in the three tillage systems was responsible for the lack of difference. Baumhardt et al. (1993) observed no differences among cotton, sorghum, and wheat cropping systems on infiltration rate in a 3-year study in Texas.

In Culbertson, MT, Pikul and Aase (1995) found no difference due to tillage or cropping system on infiltration rates, and suggested that poor soil structure and susceptibility to surface crusting were responsible for the lack of differences. TerAverest et al. (2015) in Dowa district, Malawi, reported no significant differences on infiltration rate due to tillage, residue retention, or crop rotations in a 3-year study. Dowa soil was prone to compaction and surface crusting. Our study was inconsistent with their findings that tillage did not inconsistently affect steady state infiltration rate. However, five years may not be enough time to see differences develop between NT and CT, or summer double cropping and fallow systems, especially, at the Lubbock and Thrall locations. At these locations, the previous management practices were intensive CT cotton (> 10 yrs.) which may require more years for the soil to show NT and double cropping benefits (Vogeler et al., 2009). On the contrary, TerAvest et al. (2015) found greater infiltration rate in a 3-year NT maize system than CT rotation in the Nkhotakota district, Malawi; and the greater infiltration rate was attributed to greater residue cover. Residues left on the surface of the soil after harvest in the NT maize system increased earthworm and termite populations, thus enhancing infiltration rate through preferential flow channels and splitting of surface crust (Black and Okwakol, 1997; Fragoso et al., 1997).

Nunes et al. (2018) reported a 67% increase in infiltration rate under a NT system compared to CT in a long-term study (> 20 years). This increase in infiltration rate observed could be attributed to the greater percentage of organic matter (OM), soil respiration, WAS, and active carbon in the NT compared to the CT (Nunes et al., 2018). Increasing surface residue over time improves WAS and protects the soil surface from raindrop impact, thus increasing the infiltration rate in NT (Ehlers, 1997; Ehlers and Claupein, 1994; Lampurlanes and Cantero-Martinez, 2006; Reeves, 1997). However, not all long-term studies result in greater infiltration rate for NT. For example, in Poland, Lipiec et al. (2006) in an 18 year NT study reported a decline in cumulative infiltration rate by 61% in NT compared to CT and attributed the greater infiltration rate in CT soil to greater porosity, stable aggregate structure, and greater soil moisture conditions.

Table 3.1. ANOVA table summary of significance of tillage, summer double cropping, and the interaction on single ring infiltration, Cornell infiltration at steady state, runoff rate, time-to-runoff, sorptivity, and wet aggregate stability (WAS) data at Beeville, Texas, from 2017 – 2019.

2018						
Effect	Single ring infiltration (cm h^{-1})	Cornell infiltration at steady state (cm h^{-1})	Runoff rate (cm h^{-1})	Time-to-runoff (min)	Sorptivity (cm $min^{-1/2}$)	WAS (%)
Tillage	NS	NS	NS	NS	NS	NS
Double crop	*	NS	NS	NS	NS	NS
Tillage x double crop	***	NS	*	NS	NS	NS
SEM	2.7	2.1	2.2	1.0	0.2	1.6
n	90	33	35	35	35	45
2019						
Tillage	-	NS	NS	NS	NS	NS
Double crop	-	NS	NS	NS	NS	NS
Tillage x double crop	-	NS	NS	NS	NS	NS

Table 3.1. Continued						
SEM	-	0.8	2.2	1.5	0.2	2.0
n	-	52	54	53	52	45
2020						
Tillage	NS	NS	NS	NS	NS	-
Double crop	**	NS	NS	**	*	-
Tillage x double crop	*	NS	NS	NS	NS	-
SEM	3.4	1.1	2.4	0.4	0.1	-
n	90	36	36	36	33	-

*, **, ***, Significant at the 0.05, 0.01, and 0.001 probability levels, respectively; [a]NS, not significant; SEM, standard error of mean; n, number of observations used.

Table 3.2. ANOVA table summary of significance of tillage, summer double cropping, and the interaction on single ring infiltration, Cornell infiltration at steady state, runoff rate, time-to-runoff, sorptivity, and wet aggregate stability (WAS) data at Lubbock, Texas, from 2017 – 2019.

2017						
Effect	Single ring infiltration (cm h^{-1})	Cornell infiltration at steady state (cm h^{-1})	Runoff rate (cm h^{-1})	Time-to-runoff (min)	Sorptivity (cm $min^{-1/2}$)	WAS (%)
Tillage	NS	NS	NS	NS	NS	NS
Double crop	NS	NS	NS	NS	NS	NS
Tillage x double crop	NS	**	NS	NS	NS	NS
SEM	2.9	0.9	1.3	0.5	0.1	1.6
n	89	51	53	51	49	45
2018						
Tillage	NS	NS	NS	NS	NS	NS
Double crop	NS	**	**	NS	NS	NS
Tillage x double crop	**	NS	NS	NS	NS	NS
SEM	3.6	1.8	2.7	1.1	0.1	1.8
n	90	48	50	48	49	45
2019						
Tillage	-	NS	**	NS	NS	NS
Double crop	-	NS	NS	NS	NS	NS
Tillage x double crop	-	*	*	NS	**	NS
SEM	-	2.2	3.8	0.5	0.1	3.0
n	-	54	54	54	48	45
2020						
Tillage	NS	NS	NS	NS	NS	-
Double crop	***	NS	NS	**	**	-

Table 3.2. Continued

Tillage x double crop	*	NS	NS	NS	NS	-
SEM	2.0	1.3	3.5	1.2	0.2	-
n	90	29	30	32	30	-

*, **, ***, Significant at the 0.05, 0.01, and 0.001 probability levels, respectively; [a]NS, not significant; SEM, standard error of mean; n, number of observations used.

Table 3.3. ANOVA table summary of significance of tillage, summer double cropping, and the interaction on single ring infiltration, Cornell infiltration at steady state, runoff rate, time-to-runoff, sorptivity, and wet aggregate stability (WAS) data at Thrall, Texas, from 2017 – 2019.

Effect	Single ring infiltration (cm h^{-1})	Cornell infiltration at steady state (cm h^{-1})	Runoff rate (cm h^{-1})	Time-to-runoff (min)	Sorptivity (cm $min^{-1/2}$)	WAS (%)
2017						
Tillage	***	NS	NS	**	**	NS
Double crop	NS	NS	NS	NS	*	NS
Tillage x double crop	NS	NS	NS	NS	***	NS
SEM	1.3	1.2	1.3	0.3	0.1	4.3
n	83	51	53	49	47	45
2018						
Tillage	NS	NS	NS	NS	NS	NS
Double crop	NS	NS	NS	NS	NS	NS
Tillage x double crop	NS	NS	NS	NS	NS	NS
SEM	2.8	1.0	3.7	1.5	0.2	5.8
n	88	40	46	43	39	45
2019						
Tillage	-	NS	NS	NS	NS	NS
Double crop	-	NS	NS	NS	NS	*
Tillage x double crop	-	NS	*	NS	NS	NS
SEM	-	0.8	6.4	1.1	0.1	7.8
n	-	62	72	70	70	45
2020						
Tillage	NS	NS	NS	NS	NS	-
Double crop	NS	***	NS	NS	NS	-
Tillage x double crop	NS	NS	NS	NS	NS	-
SEM	5.1	0.9	4.1	1.7	0.1	-
n	82	42	44	43	40	-

*, **, ***, Significant at the 0.05, 0.01, and 0.001 probability levels, respectively; [a]NS, not significant; SEM, standard error of mean; n, number of observations used.

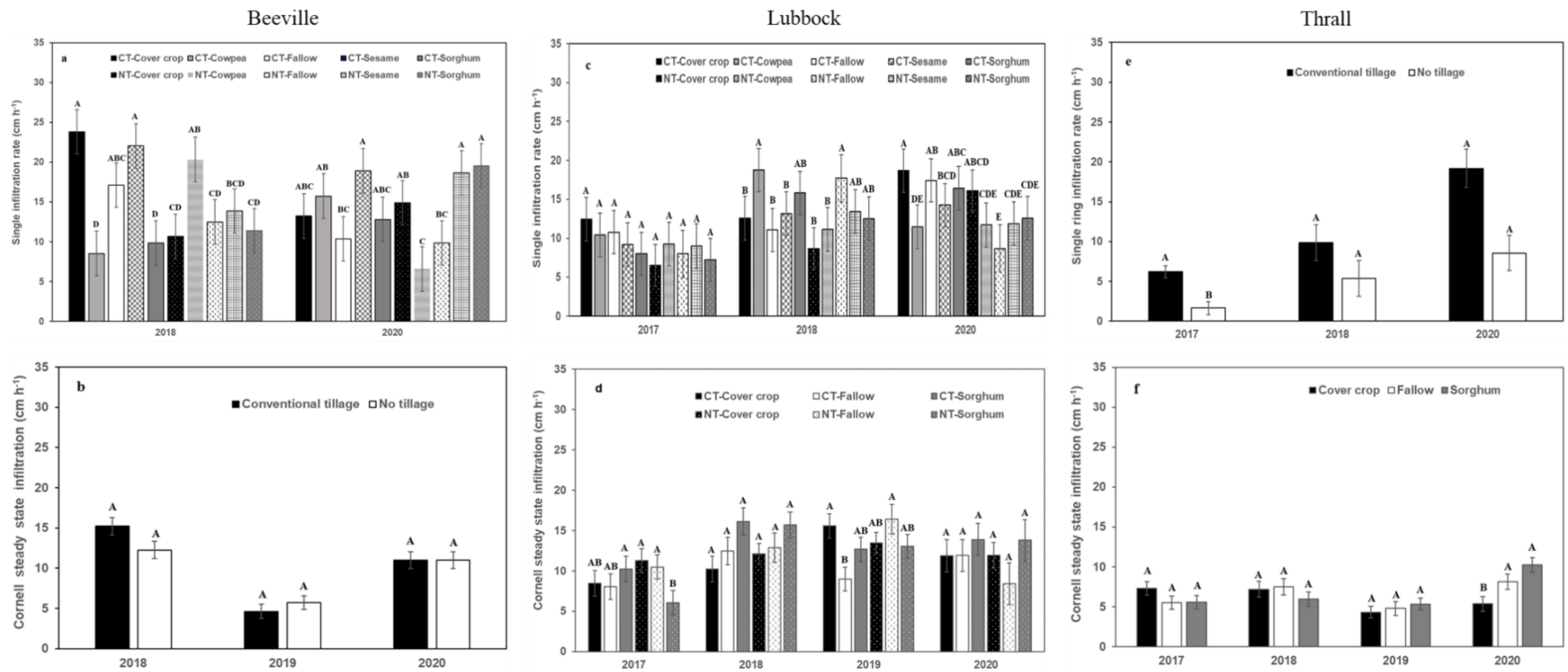

Figure 3.1. Single ring infiltration rate (cm h^{-1}), and Cornell steady state infiltration rate (cm h^{-1}), as affected by tillage, summer double cropping, tillage x summer double cropping interaction at Beeville, Lubbock and Thrall in Texas for trials initiated in 2015 (Thrall) and 2016 (Beeville and Lubbock through 2020. Bars represent standard error of mean and different letters within each year indicate significance ($P < 0.05$). CT = conventional tillage; NT = no tillage.

3.3.2. Time-to-runoff, Sorptivity, and Runoff Rates

Runoff rate was impacted by the tillage x summer double cropping interaction at Beeville, Lubbock, and Thrall (Tables 3.1, 3.2, and 3.3, Figures 3.2a, d, and g). At Beeville, runoff rate was greater in fallow under NT than fallow under CT in 2018 (Figure 3.2a). This implies that incorporating reduced tillage alone may not reduce runoff, but the combination of reduced tillage and double crops or cover crops is necessary to positively influence runoff rates at Beeville. The interaction at Lubbock in 2019 occurred because runoff rate was greater for CT-fallow, CT-sorghum, and NT-sorghum compared to NT-fallow (Figure 3.2d). The combination of reduced tillage and double cropping may not necessarily influence runoff rate at Lubbock, which was the case at Beeville. At Thrall, runoff rate was greater in fallow under CT compared to cover crop under CT in 2019 (Figure 3.2g). Time-to-runoff as measured by the Cornell sprinkle infiltrometers was only impacted by tillage in 2017 at Thrall with no differences detected at Beeville or Lubbock due to tillage practices (Tables 3.1, 3.2 and 3.3, Figures 3.2b, e, and h). In this instance, time-to-runoff was 50% greater in CT than NT plots. Crop treatment did impact time-to-runoff at Beeville and Lubbock in 2020 where sorghum was greater than fallow or cover crop treatments in both cases (Tables 3.1 and 3.2, Figures 3.2c and f).

DeLaune and Sij (2012) reported no statistical difference between NT and CT for time-to-runoff, although they found greater amount of runoff in the CT system compared to NT system. Quincke et al. (2007) in Lincoln, NE reported no differences between NT and CT on runoff rate. Soane et al. (2012) suggested that NT system over time reduced runoff due to continuous movement of earthworm burrows from the soil surface to the subsoil, and the crop residues left on the soil surface in a NT system reduced runoff. Armand et al. (2009) reported decreased runoff from NT system compared to CT and attributed crop residue left on the soil surface after harvest responsible for the reduced runoff. TerAvest et al. (2015) suggested that crop residue retention and minimal soil disturbance reduced runoff significantly and was consistent with our results at Beeville where the combination of reduced tillage and double cropping reduced runoff rate.

Sorptivity at Beeville was not significantly different for tillage throughout this study (Table 3.1). There was a tillage x summer double crop interaction at Lubbock and Thrall (Tables 3.2 and 3.3). At Lubbock, sorptivity was greater in fallow under NT than fallow under CT in 2019 (Figure 3.3b). At Thrall, sorptivity was greater for cover crop and sorghum under CT than cover crop and sorghum under NT in 2017 (Figure 3.3c). At Beeville, sorptivity was affected by summer double cropping and was greater in fallow than cover crop and sorghum in 2020(Figure 3.3a). This was expected because fallow plots were more exposed and drier compared to the cover crop and sorghum plots, thus the initial infiltration rate was greater in fallow at Beeville. Castellini et al. (2019) reported no differences between CT and NT for sorptivity in Apulia, Italy. Lipiec et al. (2006) reported greater sorptivity in CT than NT and attributed the greater sorptivity to larger aggregate porosity in the CT soil. We only observed differences in sorptivity at Thrall in 2017 and was greater in CT than NT for cover crop and sorghum. This may be due to fallow plots having greater soil moisture stored compared to cover crop and sorghum at Thrall.

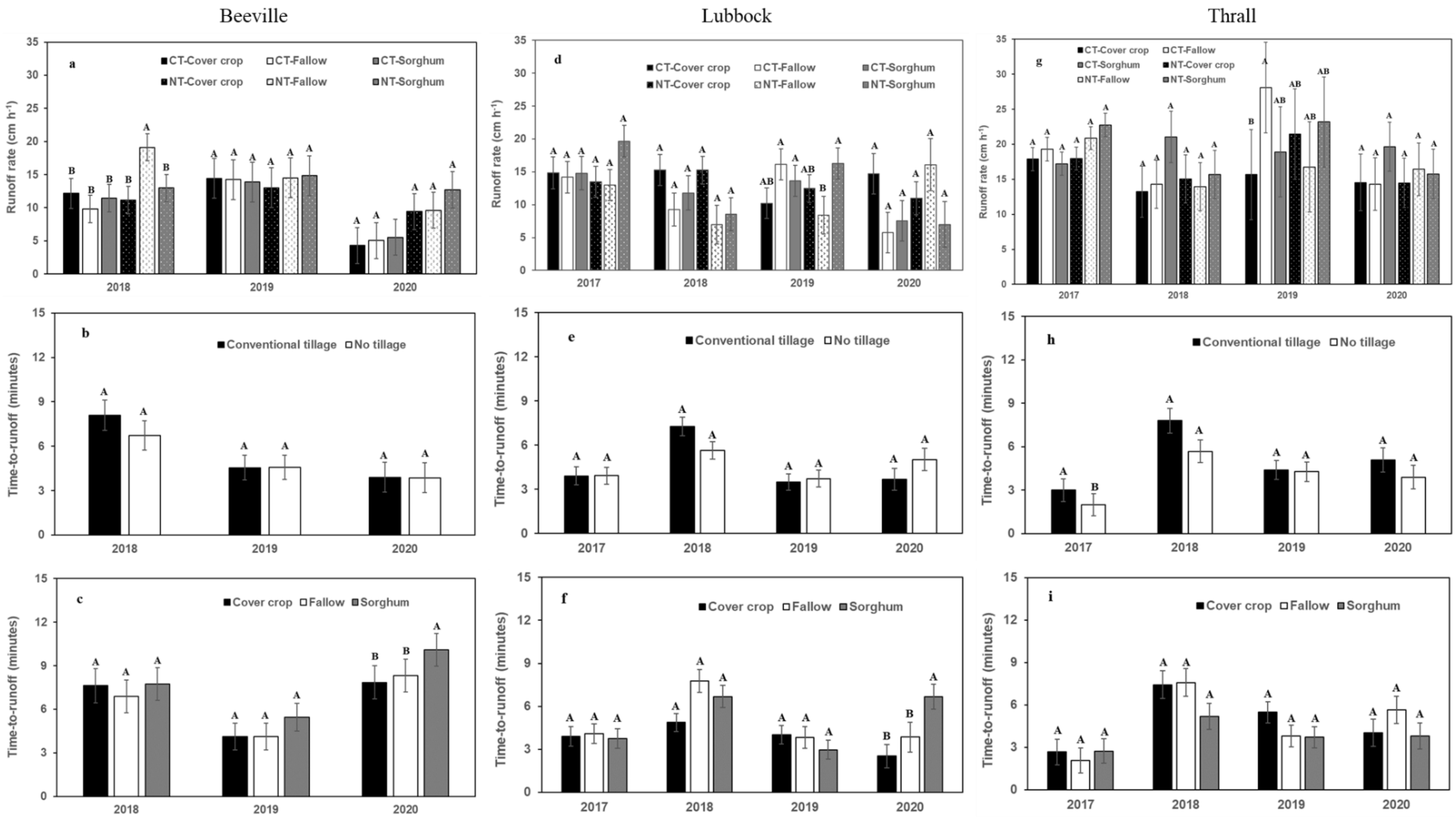

Figure 3.2. Runoff rate (cm h^{-1}), and time-to-runoff (minute) as affected by tillage x summer double cropping, tillage, and summer double cropping at Beeville, Lubbock, and Thrall in Texas for trials initiated in 2015 (Thrall) and 2016 (Beeville and Lubbock through 2020. Bars represent standard error of mean and different letters within each year indicate significance (P < 0.05). CT = conventional tillage; NT = no tillage.

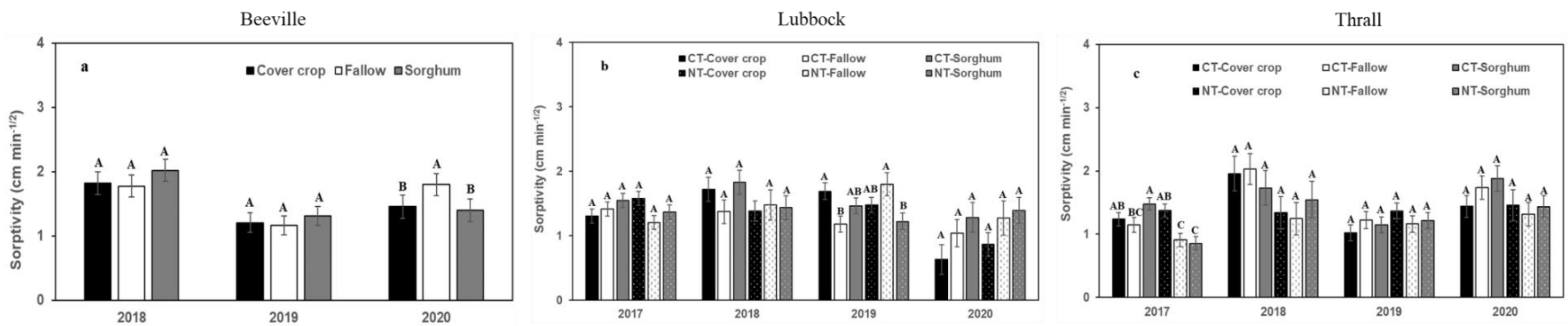

Figure 3.3. Sorptivity (cm min$^{-1/2}$) as affected by tillage, and summer double cropping, and tillage x summer double cropping interaction at Beeville, Lubbock, and Thrall in Texas for trials initiated in 2015 (Thrall) and 2016 (Beeville and Lubbock through 2020. Bars represent standard error of mean and different letters within each year indicate significance (P < 0.05).

3.3.3. Wet Aggregate Stability

Wet aggregate stability was not impacted by tillage treatments within year for any location in this study (Tables 3.1, 3.2, and 3.3, Figures 3.4a, c, and e). Wet aggregate stability generally increased over time across locations. At Beeville, WAS increased by tillage treatment from 2018 to 2019 by 12.46, 34.40, and 9.36% for CT, ST, and NT, respectively (Figure 3.4 a). At Lubbock, WAS increased for tillage treatments from 2017 to 2019 by 141.15, 57.49, and 73.23% for CT, ST, and NT, respectively (Figure 3.4c). At Thrall, WAS increased from 2017 to 2019 for tillage treatments by 26.57, 61.54, and 51.55% for CT, ST, and NT respectively (Figure 3.4e). There is possibility that the drastic increase in WAS observed from 2017 to 2019 within tillage practice to have been caused by laboratory procedures since the 2017 samples were analyzed at Cornell Soil Health Institute (Ithaca, NY, USA) while the 2018 and 2019 samples were analyzed in our laboratory at Soil and Crop Sciences, Texas A&M University, College Station. Quincke et al. (2007) in Lincoln, NE reported no differences between NT and CT for WAS, infiltration rate, and runoff rate. Gathala et al. (2011) observed no differences among tillage treatments in the first two years of a seven-year study for water stable soil aggregation and infiltration rate; however, water stable soil aggregation and infiltration rate were greater in NT than CT for the remaining five years of their study. Soils with greater WAS results in greater infiltration rates and less prone to erosion (Gathala et al., 2011). Conventional tillage management practices break down aggregates and reduce C storage in the soil that is essential for aggregate stability (Cambardella and Elliott, 1993; Gathala et al., 2011; Grandy and Robertson, 2006; Hussain et al., 1999; Jat et al., 2009; Nunes et al., 2018; Pierce et al., 1994; Singh and Malhi, 2006). In NT systems, soil aggregation increased due to little or no disturbance, leading to increases in soil OC and abundance of fungi that are critical for aggregate formation (Alvaro-Fuentes et al., 2009; Sainju et al., 2009). No tillage has the potential to increase WAS percentage over time compared to CT (Palm et al., 2013, Kassam et al., 2009), although we did not observed differences in our study yet.

Wet aggregate stability at Beeville, and Lubbock was not statistically different for summer double crop treatments (Table 3.1, and 3.2, Figures 3.4b, and d). Wet aggregate stability was statistically significant for summer double cropping at Thrall in 2019 and was greater in in cowpea (57 %) and least in fallow (45 %) (Table 3.3, Figure 3.4f). Studies have reported plant residues left after harvest of wheat or summer double crops can serve as soil surface cover and contribute to long-term WAS percentage increase and SOC (Bear et al., 1994; Gathala et al., 2011; Palm et al., 2013). Soil aggregate formation depends on the quantity and stability of OC in the soil. Stable organic matter, such as wheat straw and roots biomass in the soil are essential to aggregate stability (Six et al., 2000). Wheat-summer double crops rotations compared to wheat-fallow rotation was not statistically different for WAS in our study except at Thrall in 2019 where cowpea and sesame treatments were greater than fallow. This could be due to wheat straw and incompletely decomposed roots in the wheat-fallow system that serves as barrier and protection against raindrop impact in the soil surface (Gillabel et al., 2007; Six et al., 2000).

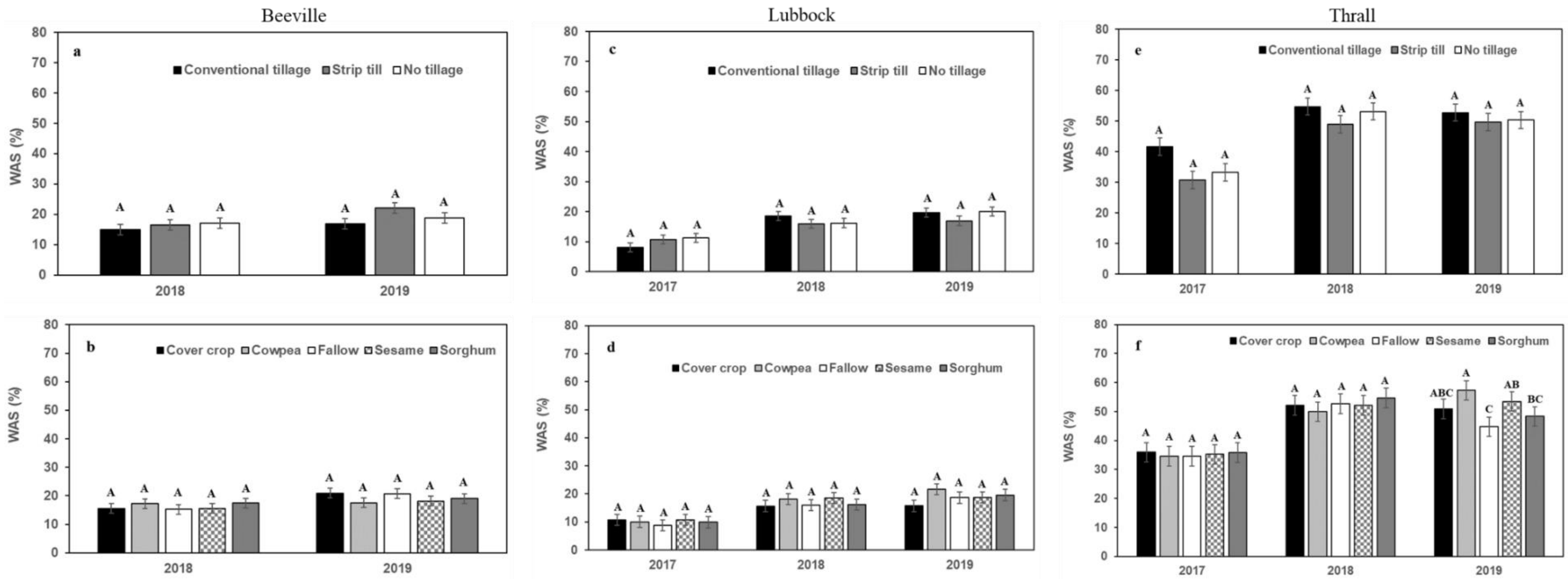

Figure 3.4. Wet aggregate stability as affected by tillage treatment and summer double crop treatment at Beeville, Lubbock, and Thrall in Texas for trials initiated in 2015 (Thrall) and 2016 (Beeville and Lubbock) through 2020. Bars represent standard error of mean and different letters within each year indicate significance ($P < 0.05$).

3.3.4. Soil Moisture Change Over Time

Stored soil moisture over time according to tillage and summer double crop treatments are presented in Figures 3.5a, 3.5b, 3.6a, 3.6b, 3.7a, and 3.7b at Beeville, Lubbock and Thrall. Moisture deficits were minimal below 60 cm when data from the full soil profile was analyzed so presented data is 0-60 cm depth. In Beeville, tillage and summer double crop treatments were significantly different for soil moisture at multiple points in time (Figures 3.5a and b). There was an interaction of tillage × summer double crops at numerous points (data not shown), and the interaction effect occurred due to low soil moisture stored in CT-sorghum combination compared to the other tillage x summer double crops combinations at numerous points in time at Beeville. No tillage (138 - 147 mm) had significantly greater stored soil moisture than CT (106 - 135 mm) during double crop growth at Beeville. However, tillage did not affect soil moisture prior to wheat planting events in the four growing seasons at Beeville. Grain sorghum utilized the most soil moisture each summer, followed by sesame especially in the summer period at Beeville. Importantly, there were moisture differences for summer double crop treatments at the time of wheat planting for two of the four growing seasons, but in the other two years the difference persisted into the wheat growing season (2018 and 2019) at Beeville. The soil moisture difference observed at Beeville at wheat planting (6 Nov. 2016) due to summer double crop treatments was greatest with cover crop (158 mm), and fallow (154 mm) treatments, and least in sorghum (133 mm), followed by sesame (143 mm), but no differences between fallow and cowpea (150 mm). On 7 Nov. 2017, soil moisture at Beeville was greatest in cover crop (146 mm), fallow (145 mm), sesame (145 mm), and cowpea (138), and least in sorghum (126 mm) (Figure 2b). The soil moisture was replenished for all treatments prior to wheat planting, mostly from precipitation, and supplementary irrigation (Chapter 2, Figure 2.1a, Figures 3.5a and 3.5b).

The low soil moisture recorded in grain sorghum treatment was likely due to greater herbage mass production compared to other summer double crop treatments (data not shown).

In Lubbock, soil moisture was impacted by tillage and double cropping (Figures 3.6a and b). Conventional tillage (88 – 152 mm) had the least amount of soil moisture stored throughout the study, while for most of the measurements; there was no difference between NT (95 – 158 mm) and ST (94 – 159 mm) at Lubbock. However, tillage did not affect soil moisture prior to wheat planting events in the four growing seasons at Lubbock. Summer double cropping impact on soil moisture was inconsistent at Lubbock. At several points where there were statistical differences during wheat or double crop growth, sesame (95 – 124 mm) treatment had the least soil moisture stored compared to the other treatments (fallow (100- 142 mm), cowpea (97 – 139 mm), cover crop (107 – 130 mm), sorghum (104 – 126 mm), sesame (95 – 124 mm) at Lubbock. In two of the four years, differences in soil moisture due summer double crop treatments were present at wheat planting in Lubbock (6 Nov. 2016 and 10 Nov. 2017), however, in every case moisture levels recovered to the fallow control by mid-winter due mostly from precipitation events (Chapter 2 Figure 2.1b, Figures 3.6a and 3.6b). Soil moisture was greatest in cowpea (132 mm) and cover crop (130 mm), and least in fallow (114 mm), followed by sesame (117 mm) and sorghum (119 mm) prior to wheat planting on 6 Nov. 2016. Soil moisture was greatest in fallow (142 mm) and cowpea (137 mm), and least in sesame (124 mm), however, sesame was not different from sorghum (126 mm) and cover crop (126 mm) prior to wheat planting on 10 Nov. 2017 (Figure 3.6b). Low soil moisture in the sesame treatments may be partly attributed to the presence of weeds in the sesame plots at Lubbock.

In Thrall, tillage and summer double cropping were significant for soil moisture (Figure 3.7a and b). For most of the year, there were no differences among tillage treatments, but when differences occurred CT had greater soil moisture compared to NT and ST treatments (Figure 3.7a). This generally correlated well with stand establishment and herbage mass production. For instance, CT had a negative impact on emergence of double crops in 2016, thus reducing stand (data not shown) and herbage mass production and using less stored soil moisture. Grain sorghum consistently used the most soil moisture every growing season, followed closely by sesame. The low soil moisture recorded in grain sorghum treatment was due to greater herbage mass production compared to the other summer double crop treatments (Chapter 2, Figure 2.5). In general, soil moisture under the cover crop and cowpea treatments were very similar to the fallow control for the entire study (Figure 3.7b), with the exception of cowpeas in summer of 2018.

Several studies have found similar results where greater soil moisture at time of planting resulted in greater crop establishment, and crop productivity (Nielsen et al., 2016; Nielson and Vigil, 2005; Nielson et al., 2002; Schlegel et al., 2017). The Beeville location was consistent with Berns and Berns (2009) where soil moisture for cover crop mixture was not different from the fallow treatment. In contrast, Nielson et al. (2016) reported greater soil moisture for fallow compared to cover crop mixture and single species. Our study demonstrated that soil moisture impact by tillage or summer double cropping treatments on wheat crop establishment and wheat productivity were inconsistent across years and locations as moisture was recovered at the time of planting principally from precipitation events. The lower soil moisture observed at Lubbock in the CT treatment may be due to evaporation, sunlight, wind, and low soil surface residue often observed in the High Plains (Massee and Cary, 1978). Lubbock has low precipitation and most of the rainfall occurred during the fall (Chapter 2, Figure 2.1b). Stone and Schlegel (2006) suggested that NT has the potential to store more moisture compared to the CT in the Great

Plains, due to its capacity to increase surface residue and minimize disturbance. Clay soil has greater water holding capacity compared to other soil textures (Brady and Weil, 1996; Osenburg and Mathews, 1951), hence, greater soil moisture in the fallow treatments were expected at Thrall location (Figure 3.7b). In Lexington, KY, Munawar et al. (1990) reported soil moisture greater in NT plots compared to CT. Other studies have shown no consistent differences between CT and NT for soil moisture in wheat production (Bouzza, 1990; Mrabet, 2000; Norwood, 2000). Overall, grain sorghum had the least soil moisture stored, followed by sesame at Beeville and Thrall, while at Lubbock, sesame had the least stored soil moisture. The low soil moisture stored in sesame crop was expected because it is a drought tolerant crop and good at extracting water (Langham et al., 2010). In most years, any deficits in soil moisture caused by treatments recovered quickly from precipitation events, and minimum irrigation applications at Beeville and Lubbock. Not surprisingly, differences were most drastic and persistent at Lubbock due to the more arid climate. Still, wheat-summer double cropping appears achievable at Beeville and Lubbock locations with only minimum irrigation. Wheat-summer double cropping rotation was successful at Thrall without supplemental irrigation, but timing of stand establishment of double crops was more variable since planting needed to be timed around precipitation events.

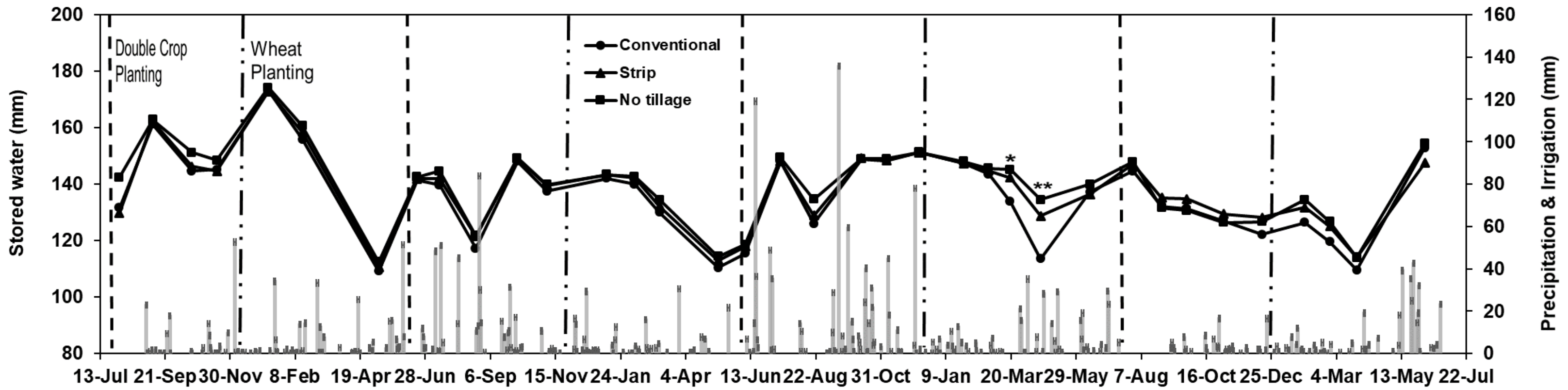

Fig. 3.5a. Soil moisture (mm) change over time as affected by tillage treatments at the Beeville, TX location (Jul. 2016 – Jun. 2020) for the 0-60 cm soil depth. * (*P*-value < 0.05) ** (*P*-value < 0.01).

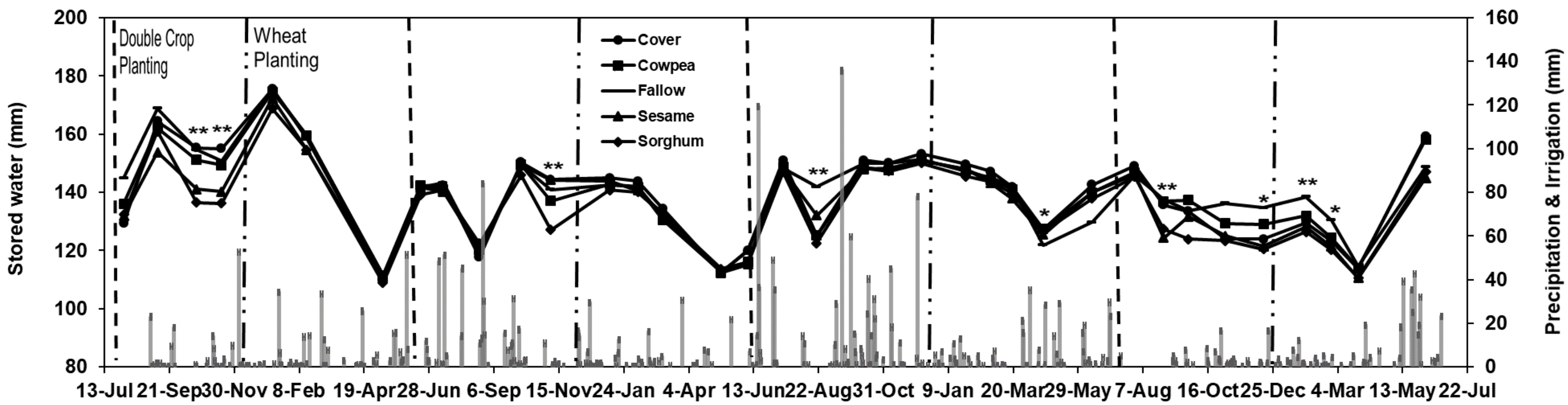

Fig. 3.5b. Soil moisture (mm) change over time as affected by double crop treatments at the Beeville, TX location (Jul. 2016 – Jun. 2020) for the 0-60 cm soil depth. * (*P*-value < 0.05) ** (*P*-value < 0.01).

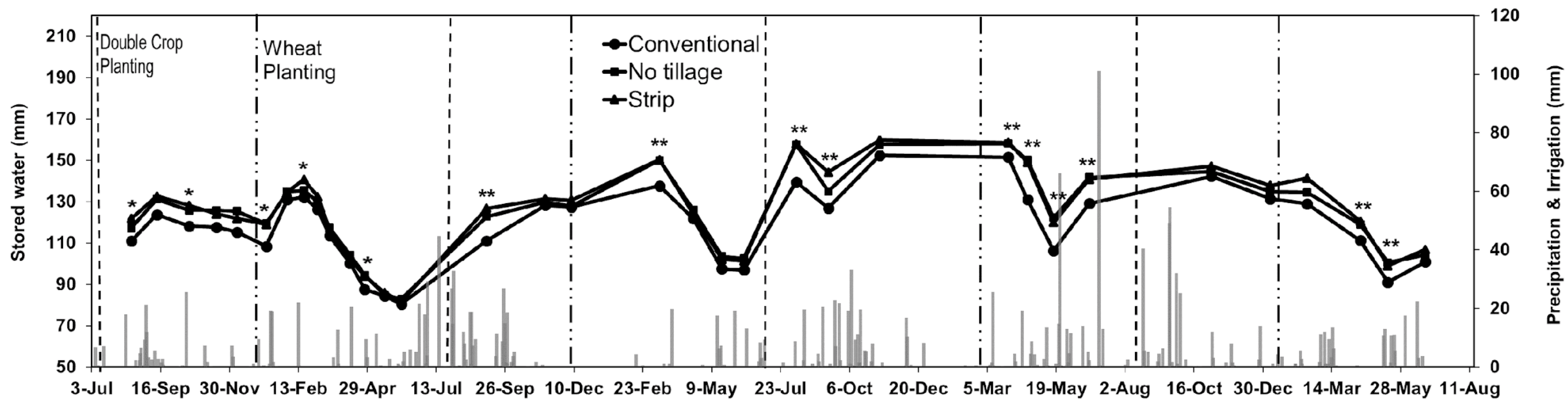

Fig. 3.6a. Soil moisture (mm) change over time as affected by tillage treatments at the Lubbock, TX location (Aug. 2016 – Jun. 2020) for the 0-60 cm soil depth. * (*P*-value < 0.05) ** (*P*-value < 0.01).

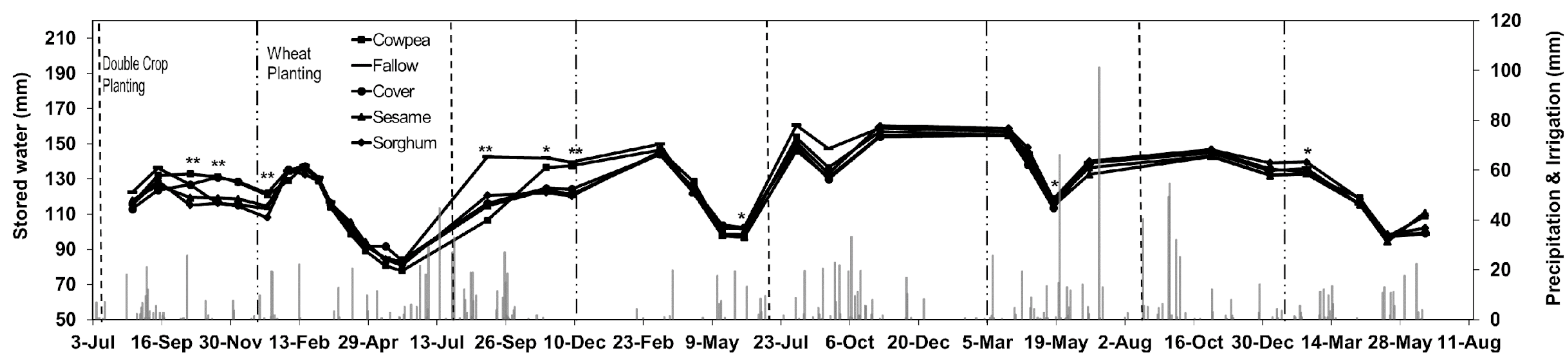

Fig. 3.6b. Soil moisture (mm) change over time as affected by double crop treatments at the Lubbock, TX location (Aug. 2016 – Jun. 2020) for the 0-60 cm soil depth. * (*P*-value < 0.05) ** (*P*-value < 0.01).

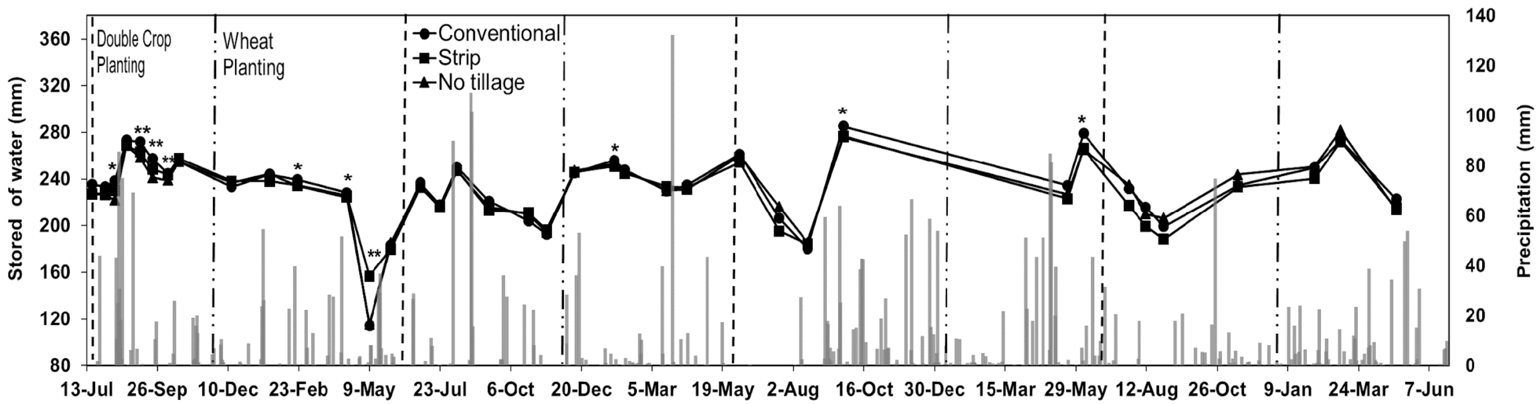

Fig. 3.7a. Soil moisture (mm) change over time as affected by tillage treatments at the Thrall, TX location (Jul. 2016 – May 2020) for the 0-60 cm soil depth. * (*P*-value < 0.05) ** (*P*-value < 0.01).

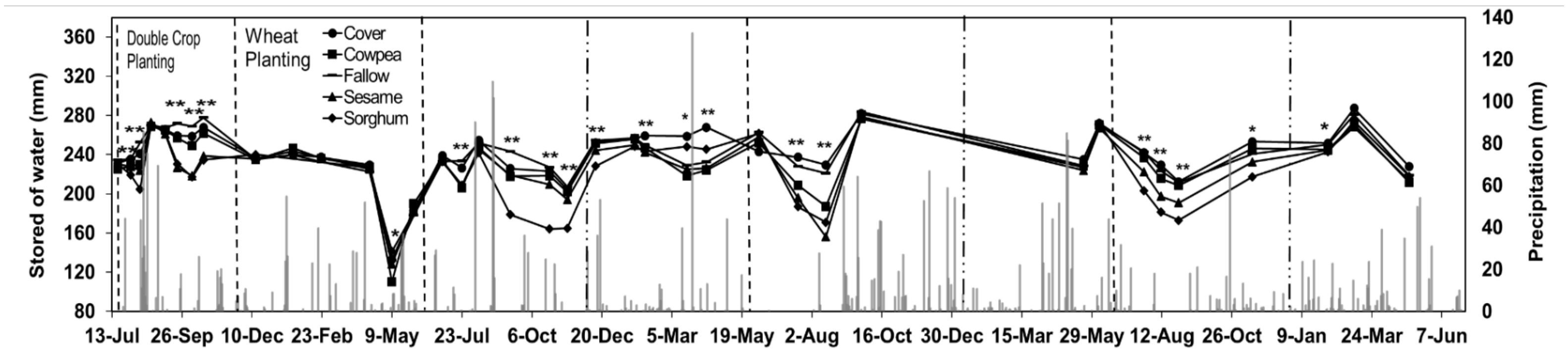

Fig. 3.7b. Soil moisture (mm) change over time as affected by double crop treatments at the thrall, tx location (jul. 2016 – may. 2020) for the 0-60 cm soil depth. * (*P*-value < 0.05) ** (*P*-value < 0.01).

3.4. Conclusions

This study focused on the short-term impact of tillage management practices and summer double cropping in wheat cropping systems on water infiltration, time-to-runoff, runoff rate, WAS, and soil moisture over time. During the five-year study, tillage and summer double cropping effects on infiltration rate, time-to-runoff, runoff rate, or WAS were minimal. However, WAS increased across all locations from 2017 to 2019. The drastic WAS increase observed from 2017 to 2019 may have been caused by changes in the laboratories where the samples were analyzed. Wet aggregate stability percentage was greater at the Thrall location and this is most likely due to the heavy clay soil in Thrall, which helps in binding SOC and soil aggregates together. Conversely, it may take years for Beeville and Lubbock WAS to increase owing to their lighter soil textures, and low precipitation and high temperature, specifically at Lubbock. It is surprising that summer double cropping has yet to increase infiltration or WAS compared to summer fallow after five years, since greater herbage mass is incorporated from the summer double crops, especially sorghum. Nevertheless, it is possible that the primary crop, wheat, may be playing the major role in improving soil physical properties, because wheat is planted annually and produces substantial herbage mass that is incorporated in all treatments as plant residues. Soil moisture was often greater in reduced tillage (NT and ST) compared to CT at Beeville and Lubbock locations, while CT was greater than NT and ST at Thrall. Still, soil moisture recovered relatively quickly prior to wheat planting events at most sites and years. Wheat-grain sorghum rotation at Beeville and Thrall, and wheat-sesame rotation at Lubbock resulted in lower soil moisture, especially in the summer for all locations. Nevertheless, wheat yield impacts were minimal as soil moisture recharged from precipitation before wheat planting. The presence of weeds in the sesame plots may have contributed to the high water usage observed at Lubbock. Grain sorghum plants produced greater biomass and use significant amounts of water when available. Soil moisture is critical for crop establishment, growth, vegetative and flowering stages. Based off our five-year study in the Coastal Plains, High Plains, and Blackland Prairie ecoregions in Texas, it will take time to see consistency and soil health improvement in the NT management and summer double cropping systems, compared to the CT-summer fallow systems common in wheat cropping systems.

3.5. References

Alexandratos, N., and J. Bruinsma. 2012. World agriculture towards 2030/2050. Land use policy 20:375.

Alvarez, R., and H.S. Steinbach. 2009. A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crop yield in the Argentine Pampas. Soil Tillage Res. 104:1–15. doi: 10.1016/j.still.2009.02.005.

Álvaro-Fuentes, J., C. Cantero-Martinez, K. López, M.V. Paustian, D. Denef, C.E. Stewart, J.L. Arrúe. 2009. Soil aggregation and soil organic carbon stabilization: Eff ects of management in semiarid Mediterranean agrosystems. Soil Sci. Soc. Am. J. 73:1519–1529. doi:10.2136/ sssaj2008.0333.

Anken, T., P. Weisskopf, U. Zihlmann, F. Hans-Rudolf, J. Jansa, and K. Perhacova. 2004. Long-term tillage system effects under moist cool conditions in Switzerland. Soil Till. Res. 78:171–-183. 10.1016/j.still.2004.02.005.

Armand, R., C. Bockstaller, A.V. Auzat, P. Van Dijk. 2009. Runoff generation related to intra-field soil surface characteristics variability. Application to conservation tillage context. Soil Till. Res. 102:27–37.

Bear, M.H., P.F. Hendrix, D. C. Coleman. 1994. Water stable aggregates and organic carbon fractions in conventional and no tillage soils. Soil Sci. Soc. Am. J. 58:777–786.

Berns, K., B. Berns. 2009. Cover crop water usage and affect on yield in no-till dryland cropping systems, final report. SARE, USDA.

Black, H.I.J., M.J.N. Okwakol. 1997. Agricultural intensification, soil biodiversity and agroecosystem function in the tropics: the role of termites. Appl. Soil Ecol., 6:37–53.

Blanco-Canqui, H., B.J. Wienhold, V.L. Jin, M.R. Schmer, L.C. Kibet. 2017. Long-term tillage impact on soil hydraulic properties. Soil Till. Res. 170:38–42.

Blanco-Canqui, H., J.D. Holman, A.J. Schlegel, J. Tatarko, and T.M. Shaver. 2013. Replacing fallow with cover crops in a semiarid soil: effects on soil properties. Soil Sci. Soc. Am. J. 77:1026–1034. doi:10.2136/sssaj2013.01.0006.

Baumhardt, R.L., J.W. Keeling, C.W. Wendt. 1993. Tillage and residue effects in infiltration into soils cropped to cotton. Agron. J. 85:379–383.

Borchers, A., E. Truex-Powell, S. Wallander, and C. Nickerson. 2014. Multi-cropping practices: recent trends in double cropping, EIB-125. U.S. Department of Agriculture, Economic Research Service, May 2014.

Bouzza, A. 1990. Water conservation in wheat rotations under several management and tillage systems in semiarid areas. Ph.D. Dissertation, University of Nebraska, Lincoln, USA. 200.

Brady, N.C., and R.R. Weil. 1996. The nature and properties of soils. Prentice-Hall. Upper Saddle River, NJ.

Cambardella, C., E. Elliott. 1993. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. Soil Sci. Soc. Am. J. 57:1071–1076. doi:10.2136/sssaj1993.03615995005700040032x.

Castellini, M., F. Fornaro, P. Garofalo, L. Giglio, M. Rinaldi, D. Ventrella, C. Vitti, A.V. Vonella. 2019. Effect of No-Tillage and Conventional Tillage on Physical and Hydraulic Properties of Fine Textured Soils under Winter Wheat. Water 11:484. doi:10.3390/w11030484.

DeLaune, P.B., J.W. Sij. 2012. Impact of tillage on runoff in long term no-till wheat systems. Soil Till. Res. 124:32–35. doi:10.1016/j.still.2012.04.009.

Dhuyvetter, K.C., C.R. Thompson, C.A. Norwood, and A.D. Halvorson. 1996. Economics of dryland cropping systems in the Great Plains: A review. J. Prod. Agric. 9:216–222.

Diskin, M.H., and N. Nazimov. 1996. Ponding time and infiltration capacity variation during steady rainfall. J. of Hydrology. 178:369–-380.

Dobberstein, J. 2014. U.S. No-Tilled Acres Reach 96 Million. No-till Farmer. Poster. https://www.no-tillfarmer.com/articles/2512-us-no-tilled-acres-reach-96-million (accessed 2 Nov. 2019).

Ehlers, W. 1997. Optimizing the components of the soil water balance by reduced and no-tillage. In: Tebrugge, F., Bo¨hrnsen, A. (Eds.), Experiences with the Applicability of No-tillage Crop Production in the West-European Countries. Proc. EC-Workshop III, Wissenschaftlicher Fachverlag, Giessen, Germany. 107–118.

Ehlers, W., W. Claupein. 1994. Approaches toward conservation tillage in Germany. In: Carter, M.R. (Ed.), Conservation Tillage in Temperate Agroecosystems. Lewis Publishers, Boca Raton, Florida, USA. 141–165.

European Commission. 2002. Communication of April 2002 from the Commission to the Council, the European Parliament, the Economic and Social Committee and the Committee of the Regions: towards a thematic strategy for soil protection [COM (2002) 179 final]. Brussels, Belgium: European Commission.

Evett, S.R., J.L. Steiner. 1995. Precision of neutron scattering and capacitance type soil water content gauges from field calibration. Soil Sci. Soc. Am. J. 59:961–968. doi:10.2136/sssaj1995.03615995005900040001x.

Foley, et al. 2011. Solutions for a cultivated planet. Nature, 478:337–342. doi:10.1038/nature10452.

Foster, J.L., M.E. Bean, C. Morgan, G. Morgan, R. Mohtar, J. Landivar, and M. Young, 2018. Comparison of two tillage practices in a semi-arid cotton–grain sorghum rotation. Agron. J. 110:1572–1579. https://doi.org/10.2134/agronj2017.12.0706

Flynn, R. 2015. Inoculation of Legumes. NMSU Coop Ext. Guide A-130. http://aces.nmsu.edu/pubs/_a/A130.pdf (accessed March 2019).

Fragoso, C., G.G. Brown, J.C. Patron, E. Blanchart, P. Lavelle, B. Pashanasi, B. Senapati, T. Kumar. 1997. Agricultural intensification, soil biodiversity and agroecosystem function in the tropics: the role of earthworms. Appl. Soil Ecol. 6:17–35.

Gathala, M.K., J.K. Ladha, Y.S. Saharawat, V. Kumar, V. Kumar, P.K. Sharma. 2011. Effect of tillage and crop establishment methods on physical properties of a medium-textured soil under a seven-year rice-wheat rotation. Soil Sci. Soc. Am. J. 75:1851–1862. doi:10.2136/sssaj2010.0362.

Gillabel, J., K. Denef, J. Brenner, R. Merckx, K. Paustian. 2007. Carbon sequestration and soil aggregation in center-pivot irrigated and dryland cultivated farming systems. Soil Sci. Soc. Am. J. 71:1020–1028. doi:10.2136/sssaj2006.0215.

Grandy, S.A., G.P. Robertson. 2006. Aggregation and organic matter protection following tillage of a previously uncultivated soil. Soil Sci. Soc. Am. J. 70:1398–1406. doi:10.2136/sssaj2005.0313.

Hobbs, P.R., K. Sayre, R. Gupita. 2007. The role of conservation agriculture in sustainable agriculture. Phil. Trans. R. Soc. B. 363:543–555. doi: 10.1098/rstb.2007.2169

Holland, J.M. 2004. The environmental consequences of adopting conservation tillage in Europe: reviewing of the evidence. Agriculture, Ecosystems and Environment, 103:1–25.

Holman, J.D., Y. Assefa, A.K. Obour. 2020. Cover-crop water use and productivity in the high plains wheat–fallow crop rotation. Crop Sci. 2020:1–12. doi:10.1002/csc2.20365.

Hussain, I., K.R. Olson, J.C. Siemens. 1999. Long-term tillage eff ects on soil chemical properties and organic matter fractions. Soil Sci. Soc. Am. J. 63:1335–1341. doi:10.2136/sssaj1999.6351335x.

Jat, M.L., M.K. Gathala, J.K. Ladha, Y.S. Saharawat, A.S. Jat, V. Kumar, S.K. Sharma, V. Kumar, R.K. Gupta. 2009. Evaluation of precision land leveling and double zero-till systems in the rice-wheat rotation: Water use, productivity, profitability and soil physical properties. Soil Till. Res. 105:112–121. doi:10.1016/j.still.2009.06.003.

Kahlon, M.S., Lal, R., and Ann-Varughese, M., 2013. Twenty two years of tillage and mulching impacts on soil physical characteristics and carbon sequestration in Central Ohio. Soil Till. Res. 126:151–158.

Kassam, A., T. Friedrich, F. Shaxson, J. Pretty. 2009. The spread of conservation agriculture: justification, sustainability, and uptake. Int. J. Agric. Sustain. 7:292–320.

Keeling, W., E. Segerra, and J.R. Abernathy, J.R. 1989. Evaluation of conservation tillage cropping systems for cotton on the Texas High Plains. J. Prod. Agric. 2:269–273. doi:10.2134/jpa1989.0269.

Kibblewhite, M.G., K. Ritz, and M.J. Swift. 2008. Soil health in agricultural systems. Phil. Trans. R. Soc. B. 363:685–701 doi:10.1098/rstb.2007.2178.

Lal, R. 2001. Soil degradation by erosion. Land Deg. Dev. 12:519–539. doi:10.1002/ldr.472.doi:10.1002/ldr.472.

Lampurlanes, J., C. Cantero-Martınez. 2006. Hydraulic conductivity, residue cover, and soil surface roughness under tillage systems in semi-arid conditions. Soil Till. Res. 85:13–26.

Langham D.R., J. Riney, G. Smith, T. Wiemers, D. Pepper, and T. Speed. 2010. Sesame Producers Guide. Sesaco Corp.

Lipiec, J., J. Kus, A. Slowinska-Jurkirwicz, A. Nosalewicz. 2006. Soil porosity and water infiltration as influenced by tillage methods. Soil Till. Res. 89:210–220.

Massee, T.W., and J.W. Cary. 1978. Potential for reducing evaporation from summer fallow. J. Soil Water Conserv. 33:126–129. https://eprints.nwisrl.ars.usda.gov/337/1/403.pdf (accessed 6 July 2020).

Munawar, A., R.L. Blevins, W.W. Frye, M.R. Saul. 1990. Tillage and Cover Crop Management for Soil Water Conservation. Agron. J. 82:773–777.

Mrabet, R. 2000. Differential response of wheat to tillage management systems in a semiarid area of Morocco. Field Crop Res. 66:165–174. PII: S0378-4290(00)00074-5.

National Oceanic and Atmospheric Administration (NOAA). 2020. https://www.noaa.gov/ (accessed 4 July. 2020).

Nielsen D.C., D.J. Lyon, R.K. Higgins, G.W. Hergert, et al. 2016. Cover crop effect on subsequent wheat yield in the central Great Plains. Agron J 108:243–256.

Nielsen, D.C., P.W. Unger, P.R. Miller. 2005. Efficient water use in dryland cropping systems in the Great Plains. Agron. J. 97:364–372. https://www.ars.usda.gov/ARSUserFiles/30100000/2005Documents/2005/420%202005%20Nielsen%20Agron%20J.pdf (accessed 15 June 2020).

Nielsen, D.C., M.F. Vigil, R.L. Anderson, R.A. Bowman, J.G. Benjamin, A.D. Halvorson. 2002. Cropping system influence on planting water content and yield of winter wheat. Agron. J. 94:962–967. doi:10.2134/agronj2002.0962.

Norwood, C.A., A.J. Schlegel, D.W. Morishita, and R.E. Gwin. 2013. Cropping system and tillage effects on available soil water and yield of grain sorghum and winter wheat. J. Prod. Agric. 3:356–362.

Nunes, M.R., H.M. van Es, R. Schindelbeck, A.J. Ristow, M. Ryan. 2018. No-till and cropping system diversification improve soil health and crop yield. Geoderma 328:30–43. doi:10.1016/j.geoderma.2018.04.031.

Osenburg, A., O.R. Mathews. 1951. Dryalnd crop production on the clay soils of western South Dakota. South Dakota Agr. Exp. Sta. Cir. Paper 82.

Palm, C., H. Blanco-Canqui, F. DeClerck, L. Gatere, P. Grace. 2013. Conservation agriculture and ecosystems services: an overview. Agric. Ecosyst. Environ. 187:87–105.

Pierce, F.J., M.C. Fortin, M.J. Staton. 1994. Periodic plowing effects on soil properties in a no-till farming system. Soil Sci. Soc. Am. J. 58:1782–1787. doi:10.2136/sssaj1994.03615995005800060029x.

Pikul Jr., J.L., J.K. Aase. 1995. Infiltration and soil properties as affected by annual cropping in the Northern Great Plains. Agron. J. 87:656–662.

Pittelkow, C.M., X. Liang, B.A. Linquist, K.J. Van Groenigen, J. Lee, M.E. Lundy, N. Van Gestel, J. Six, R.T. Venterea, and C. van Kessel. 2015. Productivity limits and potentials of the principles of conservation agriculture. Nature 517:365–368.

Quincke, J.A., C.S. Wortmann, M. Mamo, T. Franti, R.A. Drujber, J.P. Garcia. 2007. One-time tillage of no-till systems: soil physical properties, phosphorus runoff, and crop yield. Agronomy Journal 99:1104–1110.

Reeves, D.W. 1997. The role of organic matter in maintaining soil quality in continuous cropping systems. Soil Till. Res. 43:131–167.

Sainju, U.M., T. Caesar-TonThat, J.L. Jabro. 2009. Carbon and nitrogen fractions in dryland soil aggregates aff ected by long-term tillage and cropping sequences. Soil Sci. Soc. Am. J. 73:1488–1495. doi:10.2136/sssaj2008.0405.

SAS Institute. 2010. SAS/STAT 9.22 user's guide. SAS Inst., Cary, NC.

Savabi, M.R., M.H. Golabi, A.A. Abou-Arab, E.J. Kladivko. 2007. Infiltration characteristics of no-till vs conventional tillage in Indiana and Illinois farm fields. 289–299. In T. Goddard et al. (ed.) No-till farming systems. Spec. Publ. 3. World Association of Soil and Water Conservation, Tokyo.

Schlegel, A.J., Y. Assefa, L.A. Haag, C.R. Thompson, J.D. Holman, L.R. Stone. 2017. Yield and soil water in three dryland wheat and grain sorghum rotations. Agron. J. 109:227–238.

Singh, B., S.S. Malhi. 2006. Response of soil physical properties to tillage and residue management on two soils in a cool temperate environment. Soil Till. Res. 85143–153. doi:10.1016/j.still.2004.12.005.

Six, J., E. Elliott, K. Paustian. 2000. Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under notillage agriculture. Soil Biol. Biochem. 32:2099–2103. doi:10.1016/ S0038-0717(00)00179-6.

Soane, B.D., B.C. Ball, J.A. Arvidsson, G. Basch, J. Roger-Estrade. 2012. No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. Soil and Till. Res. 188:66–87. doi:10.1016/j.still.2011.10.015.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at the following link: http://websoilsurvey.sc.egov.usda.gov/. (accessed 16 March 2021).

Stone, L.R., and A.J. Schlegel. 2006. Yield-water supply relationships of grain sorghum and winter wheat. Agron. J. 98:1359–1366.

Tebrugge, F., and R.A. During. 1999. Reduced tillage intensity – a review of results from a long-term study in Germany. Soil & Till. Res. 53:15–28. doi:10.1016/S0167-1987(99)00073-2.

TerAvest, D., L. Carpenter-Boggs, C. Thierfelder, J.P. Reganold. 2015. Crop production and soil water management in conservation agriculture, no-till, and conventional tillage systems in Malawi. Agric., Ecosys. and Environ. 212:285–296. doi:10.1016/j.agee.2015.07.011.

Unger, P.W. 1984. Tillage and residue effects on wheat, sorghum and sunflower grown in rotation. Soil Sci. Soc. Am. J. 48:1423–1432.

USDA-NASS. 2020. Small Grains 2020 Summary. ISSN: 1949-162X. https://downloads.usda.library.cornell.edu/usda-esmis/files/5t34sj573/7p88d6171/bn999x131/smgr0920.pdf (accessed 30 October 2020).

USDA-NRCS. 2001. Soil Quality Test Kit Guide. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_050956.pdf (accessed 20 Jan. 2019).

van Es, H.M., R.R. Schindelbeck. 2003. Field procedures and data analysis for the Cornell sprinkle infiltrometer. Cornell University. https://cpb-use1.wpmucdn.com/blogs.cornell.edu/dist/f/5772/files/2015/11/Cornell-Sprinkle Infiltrometer-manual-1xf0snz.pdf (accessed 18 Jan. 2019).

Vogeler, I., J. Rogasik, U. Funder, K. Panten, E. Schnug. 2009. Effect of tillage systems and P-fertilization on soil physical and chemical properties, crop yield and nutrient uptake. Soil Till. Res. 103:137–143.

CHAPTER IV

CONCLUSIONS

After five years of wheat, and four years of summer double crop seasons, our results showed that, reduced tillage systems such as NT and ST and summer double cropping are possible in the Coastal Plains, and Blackland Prairie ecoregions. This is only possible in the High Plains with sufficient irrigation and short season crops or cultivars. Tillage affected wheat establishment, wheat grain and herbage mass and was inconsistent across years and ecoregions. Summer double cropping also affected wheat establishment, wheat grain yield, and herbage mass differently across ecoregions, but ultimately showed limited negative impacts on wheat grain yield. This study addressed some of the concerns of wheat growers about NT and summer double cropping, such as water availability, poor stands and low yields. For instance, at Thrall, without irrigation NT yields were comparable to the CT. However, wheat-summer double cropping rotations in the High Plains will be very difficult to achieve due to the necessity of irrigation for the summer crop. Overall, there were minimal differences due to tillage or summer double cropping systems for crop grain yields and herbage mass. This indicates that some of these conservation management practices may be successfully implemented across the three ecoregions in Texas. Iron and Clay cowpea, pearl millet, guar, lablab are possible cover crop multi-species combination that can be considered in the three ecoregions. However, summer double cropping such as sorghum and sesame may improve producers' annual net return over cover crops

After five years of study, tillage and summer double cropping resulted in minimal impact on infiltration rate, runoff rate, sorptivity, time-to-runoff, and wet aggregate stability. Across locations, WAS tended to increase over time from 2017 to 2019. We expected NT and summer double cropping to increase infiltration rate and WAS, however this was not the case. We perceived that the wheat crop may be playing a significant role in enhancing the soil physical properties due to greater residues produced from the wheat crop. Soil moisture was greater in NT and ST than CT at Beeville and Lubbock, while at Thrall CT stored more soil moisture than NT and ST. However, the impact on wheat yield was minimal because soil moisture recovered prior to wheat from precipitation events. Wheat-sorghum rotation utilized the greatest soil moisture at Beeville and Thrall, while at Lubbock; wheat-sesame rotation used more water than all other summer double crops. Grain sorghum produces greater herbage mass and can utilize water when available. The presence of weeds in the sesame plots may have contributed to high water utilization at Lubbock.

Based off our five-year study in the three ecoregions in Texas, conservation management practices such as NT, ST, and summer double cropping may take time to show consistent soil health improvement. Future research should focus on on-farm trials and implementation of some selected wheat-summer double cropping rotations across Texas to validate our study. An economic analyses is critical in determining the value of transitioning from CT-summer fallow to conservation tillage and summer double cropping in the short and long-term in Texas.

APPENDIX A

SUPPLEMENTARY DATA

Table A.1. Herbicides and insecticides application expressed in active ingredient (a.i.) to control weeds in wheat and summer double crops stands for 2016, 2017, 2018, 2019, and 2020 for each location.

Year	Crop	Item	Active ingredient (a.i.)	Application date	Rate (kg a.i. ha^{-1})
Beeville					
2015	Wheat	Herbicide	Saflufenacil: N'-[2-chloro-4-fluoro-5-(3-methyl-2,6-dioxo-4-(trifluoromethyl)-3, 6-dihydro-1(2H)-pyrimidinyl)benzoyl]-N-isopropyl-N-methylsulfamide; Sharpen	19 Nov	0.053
	Wheat	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup WeatherMax	19 Nov	2.378
	Wheat	Herbicide	Sulfosulfuron; Outrider	17 Dec	0.0002
2016	Wheat	Herbicide	Dimethylamine salt of 2-methyl-4-chlorophenoxyacetic acid; MCPA Amine	4 Feb	0.401
	Wheat	Herbicide	Thifensulfuron-methyl (33.33 %) and Tribenuron-methyl (16.67 %); Harmony Extra SG	4 Feb	0.0016 & 0.0008
	Wheat	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup WeatherMax	21 Mar	2.378
	Double crop	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup WeatherMax	13 May	2.378
	Double crop	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup WeatherMax	16 Jun	2.378
	Double (not cover crop)	Herbicide	S-metolachlor; Dual II Magnum	16 Jun	1.544
	Double crop	Herbicide	Glufosinate-ammonium*; Ignite 280 SL	14 Jun	0.611
	Double crop	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup WeatherMax	19 Aug	3.347

Table A.1. Continued

	Double crop (not sesame)	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup WeatherMax	2 Sep	1.586
	Sesame	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup WeatherMax	8 Nov	0.024
	Cover crop (Sunn hemp)	Herbicide	2, 4-D Amine	8 Nov	0.047
	Wheat	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup WeatherMax	1 Dec	2.378
2017	Double crop (not cover crop)	Herbicide	S-metolachlor; Dual II Magnum	1 Jun	1.544
	Double crop	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup PowerMax	12 Jun	2.378
	Double crop: fallow, alleys	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup PowerMax	12 Jul	0.024
	Sorghum	Insecticide	Sulfoxaflor, Transform WG	Aug	0.050
	Wheat	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup PowerMax	21 Nov	1.586
2018	Wheat	Herbicide	Dicamba salt (12.4 %) and 2, 4-D amine salt (35.7 %); WeedMaster	30 Jan	0.018 & 0.052
	Double crop (not cover crop)	Herbicide	S-metolachlor; Dual II Magnum	20 May	1.459
	Double crop	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup WeatherMax	30 May	2.378
	Double crop	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup WeatherMax	25 Jun	2.378
	Double crop	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup WeatherMax	11 Jul	2.378

Table A.1. Continued

	Double crop (not cover crop)	Herbicide	S-metolachlor; Dual II Magnum	11 Jul	1.459
	Sorghum and cowpea	Insecticide	Zeta-Cypermethrin* (3.75 %), Bifenthrin** (11.25 %); Hero	10 Aug	0.067
	Double crop	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup WeatherMax	20 Aug	1.586
	Double crop	Herbicide	Fluazifop-P-butyl; Fusilade II	20 Aug	0.216
	Double crop	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup WeatherMax	28 Aug	1.586
	Double crop	Herbicide	Fluazifop-P-butyl; Fusilade II	28 Aug	0.216
	Double crop	Herbicide	Glufosinate-ammonium*; Liberty	13 Sep	0.481
	Double crop	Herbicide	Glufosinate-ammonium*; Liberty	24 Sep	0.481
	Double crop	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup WeatherMax	30 Oct	2.378
	Double crop	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup WeatherMax	21 Nov	2.378
	Wheat	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup WeatherMax	12 Dec	2.378
	Wheat	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup PowerMax	18 Dec	1.586
	Wheat	Herbicide	Saflufenacil: N'-[2-chloro-4-fluoro-5-(3-methyl-2,6-dioxo-4-(trifluoromethyl)-3, 6-dihydro-1(2H)-pyrimidinyl)benzoyl]-N-isopropyl-N-methylsulfamide; Sharpen	18 Dec	0.051
2019	Wheat	Herbicide	S-metolachlor; Dual II Magnum	12 Feb	1.459
	Wheat	Herbicide	Glufosinate-ammonium*; Liberty	12 Feb	0.481
	Wheat	Herbicide	S-metolachlor; Dual II Magnum	27 Feb	1.459
	Wheat	Herbicide	Glufosinate-ammonium*; Liberty	27 Feb	0.481

Table A.1. Continued

	Wheat	Herbicide	Dimethylamine salt of 2-methyl-4-chlorophenoxyacetic acid; MCPA Amine	5 Mar	0.533
	Wheat	Herbicide	S-metolachlor; Dual II Magnum	10 Apr	1.459
	Wheat	Herbicide	Glufosinate-ammonium*; Liberty	10 Apr	0.481
	Double crop (not cover crop)	Herbicide	S-metolachlor; Dual II Magnum	3 Jun	1.459
	Double crop	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup PowerMax	3 Jun	2.378
	Cowpea	Herbicide	Clethodim; Clethodim 2E	14 Jun	0.144
	Double crop	Herbicide	Glufosinate-ammonium*; Liberty	7 Aug	0.722
	Fallow	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup PowerMax	7 Aug	2.378
	Wheat	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup PowerMax	20 Oct	2.378
	Wheat	Herbicide	*Gylphosate, N-(phosphonomethyl) glycine; Roundup WeatherMax	6 Dec	2.378
	Wheat	Herbicide	Sulfosulfuron; Outrider	6 Dec	0.000
	Wheat	Herbicide	Dimethylamine salt of 2-methyl-4-chlorophenoxyacetic acid; MCPA Amine	6 Dec	0.401
	Wheat	Herbicide	Saflufenacil: N'-[2-chloro-4-fluoro-5-(3-methyl-2,6-dioxo-4-(trifluoromethyl)-3, 6-dihydro-1(2H)-pyrimidinyl)benzoyl]-N-isopropyl-N-methylsulfamide; Sharpen	6 Dec	0.053
Lubbock					
2016	Double crop	Herbicide	Gylphosate, N-(phosphonomethyl) glycine; Roundup PowerMax	14 Jun	2.378
	Double crop	Herbicide	Fluroxypyr as the methyl heptyl ester 200 g/L; Tomahawk	17 Jun	0.735
	Double crop	Herbicide	S-metolachlor; Dual II Magnum	24 Jun	1.431

Table A.1. Continued

	Sorghum	Herbicide	2-chloro-4,6-bis 9isopropylamino)-s-triazine; Milo-Pro	24 Jun	1.153
	Double crop	Herbicide	Gylphosate, N-(phosphonomethyl) glycine; Roundup PowerMax	27 Jun	2.378
	Sorghum	Insecticide	Lambda-cyhalothrin (4.63 %), Chlorantraniliprole (9.26 %); Besiege	Aug	0.290
2017	Fallow, alleys	Herbicide	Gylphosate, N-(phosphonomethyl) glycine; Roundup PowerMax	9 Aug	2.378
	Fallow, alleys	Herbicide	Glufosinate-ammonium*; Liberty 280 SL	9 Aug	0.908
	Cowpea, fallow	Herbicide	Gylphosate, N-(phosphonomethyl) glycine; Roundup PowerMax	13 Oct	2.378
	Wheat	Herbicide	Fluroxypyr as the methyl heptyl ester 200 g/L; Tomahawk	15 Nov	0.735
	Sorghum	Insecticide	Flupyradifurone*; Sivanto 200 SL	Aug	0.820
2018	Double crop	Herbicide	Paraquat dichloride (1,1'-dimethyl-4,4'bipyridinium dichloride); Gramoxone SL 2.0	3 Jul	1.192
	Double crop	Herbicide	Paraquat dichloride (1,1'-dimethyl-4,4'bipyridinium dichloride); Gramoxone SL 2.0	2 Aug	1.192
	Double crop	Herbicide	Dimethenamid-P: (S)-2-chloro-N-[(1-methyl-2-methoxy)ethyl]-N-(2,4-dimethyl-thien-3-yl)-acetamide; Outlook	2 Aug	0.971
2019	Wheat	Herbicide	2, 4-D Amine	18 Jan	0.221
	Wheat	Herbicide	Glyphosate, N-(phosphonomethyl)glycine; Gly Star	4 Feb	1.943
	Wheat	Herbicide	2, 4-D Amine	25 Apr	0.221

Table A.1. Continued

	Double crop	Herbicide	Paraquat dichloride (1,1'-dimethyl-4,4'bipyridinium dichloride); Gramoxone SL 2.0	29 Jun	0.795
	Double crop	Herbicide	Paraquat dichloride (1,1'-dimethyl-4,4'bipyridinium dichloride); Gramoxone SL 2.0	21 Jul	0.994
	Double crop	Herbicide	S-metolachlor; Dual II Magnum	9 Aug	1.512
Thrall					
2016	Wheat	Herbicide	Pyrasulfotole (3.3 %), Bromoxynil Octanoate (13.4 %), Bromoxynil Heptanoate (12.9 %); Huskie	6 Jan	0.04 & 0.24
	Double crop	Herbicide	Glyphosate, N-(phosphonomethyl)glycine; Gly Star Plus	15 Jun	1.153
	Double crop (not sesame)	Herbicide	S-metolachlor; Dual II Magnum	15 Jun	1.101
	Sorghum	Insecticide	Flupyradifurone*; Sivanto 200 SL	Aug	0.820
	Double crop: fallow, cowpea, cover crop	Herbicide	Glyphosate, N-(phosphonomethyl)glycine; Gly Star Plus	9 Sep	1.153
	Cover crop	Herbicide	Glyphosate, N-(phosphonomethyl)glycine; Gly Star Plus	12 Oct	1.153
	Wheat	Herbicide	Glyphosate, N-(phosphonomethyl)glycine; Gly Star Plus	20 Dec	1.153
	Wheat	Herbicide	Saflufenacil: N'-[2-chloro-4-fluoro-5-(3-methyl-2,6-dioxo-4-(trifluoromethyl)-3, 6-dihydro-1(2H)-pyrimidinyl)benzoyl]-N-isopropyl-N-methylsulfamide; Sharpen	20 Dec	0.411

Table A.1. Continued

2017	Wheat	Herbicide	Thifensulfuron-methyl (33.33 %) and Tribenuron-methyl (16.67 %); Harmony Extra SG	1 Feb	0.0016 & 0.0008
	Double crop	Herbicide	Glyphosate, N-(phosphonomethyl)glycine; Gly Star Plus	23 Jun	1.153
	Double crop	Herbicide	S-metolachlor; Dual II Magnum	23 Jun	1.101
	Double: fallow, cowpea, cover crop	Herbicide	Glyphosate, N-(phosphonomethyl)glycine; Gly Star Plus	1 Aug	1.153
	Sorghum	Insecticide	Flupyradifurone*; Sivanto 200 SL	Aug	0.820
2018	Double crop	Herbicide	Dimethenamid-P: (S)-2-chloro-N-[(1-methyl-2-methoxy)ethyl]-N-(2,4-dimethyl-thien-3-yl)-acetamide; Outlook	2 Jul	0.755
	Cowpea, sesame, and fallow	Herbicide	Fluazifop-P-butyl; Fusilade II	2 Jul	0.180
2019	Wheat	Herbicide	Gylphosate, N-(phosphonomethyl) glycine; Roundup PowerMax	31 Jan	2.176
	Wheat	Herbicide	Saflufenacil: N'-[2-chloro-4-fluoro-5-(3-methyl-2,6-dioxo-4-(trifluoromethyl)-3, 6-dihydro-1(2H)-pyrimidinyl)benzoyl]-N-isopropyl-N-methylsulfamide; Sharpen	31 Jan	0.051
	Wheat	Herbicide	Gylphosate, N-(phosphonomethyl) glycine; Roundup PowerMax	18 Dec	1.583

Table A.2. Wheat stand count, grain yield, and herbage mass by tillage treatment, and summer double crop treatment effects within year at Beeville location in Texas.

Beeville	Wheat stand count (plants m^{-2})				
Tillage	2016	2017	2018	2019	2020
CT§	-	153 a†	249	94 a	485
ST	-	119 b	304	61 b	467
NT	-	108 b	262	47 c	492
SEM		43	43	43	43
Double crop					
Fallow	-	120	269	64	495
Cowpea	-	143	293	67	480
Sorghum	-	110	262	56	481
Sesame	-	137	277	74	485
Cover Crop	-	123	258	74	468
SEM	-	33	33	33	33
	Wheat grain yield (kg ha^{-1})				
	2016	2017	2018	2019	2020
CT	-	-	2812	2010	2199 b
ST	-	-	2593	1447	2421 ab
NT	-	-	2681	1077	3061 a
SEM			221	221	221
Fallow	-	-	2746 ab	1338 ab	3871 a
Cowpea	-	-	2648 ab	1794 a	2673 b
Sorghum	-	-	2542 b	1247 b	1839 b
Sesame	-	-	2861 a	1623 ab	2472 b
Cover Crop	-	-	2681 ab	1556 ab	1946 b
SEM	-	-	265	265	265
	Wheat herbage mass (kg ha^{-1})				
	2016	2017	2018	2019	2020
CT	-	2750	6405	6177	3298
ST	-	2553	6149	5082	3632
NT	-	3118	6114	4089	4591
SEM		474	474	474	474
Fallow	-	2581	6546	4524	5806 a
Cowpea	-	3143	6169	4453	4010 b
Sorghum	-	2816	5616	5223	2758 b
Sesame	-	2361	6482	5560	3709 b
Cover Crop	-	3134	6299	5820	2919 b
SEM	-	478	478	478	478

†Means within a column followed by different letters (a-c) within the same category are different statistically ($p < 0.05$).

§CT = conventional tillage; NT = no-till; and ST = strip till.

Table A.3. Wheat stand count, grain yield, and herbage mass by tillage treatment, and summer double crop treatment effects within year at Lubbock location in Texas.

Lubbock	Wheat stand count (plants m^{-2})				
Tillage	2016	2017	2018	2019	2020
CT§	-	149 b†	96	171 a	121 a
ST	-	166 a	102	143 b	105 ab
NT	-	149 b	102	135 b	84 b
SEM		9	9	9	9
Double crop					
Fallow	-	148	100	145	87 b
Cowpea	-	160	103	156	90 b
Sorghum	-	153	109	144	113 a
Sesame	-	159	93	152	107 ab
Cover Crop	-	153	94	151	120 a
SEM	-	10	10	10	10
	Wheat grain yield (kg ha^{-1})				
	2016	2017	2018	2019	2020
CT	-	951b	722	1895 a	3276
ST	-	1861 a	795	815 b	3153
NT	-	1455 ab	617	729 b	2668
SEM		230	230	230	230
Fallow	-	1339 ab	728	1151	2984 b
Cowpea	-	1742 a	679	1329	2665 b
Sorghum	-	1007 b	736	1094	4114 a
Sesame	-	1261 b	728	1021	2728 b
Cover Crop	-	1763 a	686	1138	2670 b
SEM	-	173	173	173	173
	Wheat herbage mass (kg ha^{-1})				
	2016	2017	2018	2019	2020
CT	-	2787	2612 b	3951 a	5956
ST	-	3413	3771 a	2040 b	5753
NT	-	3441	3836 a	2276 b	4856
SEM		395	395	395	395
Fallow	-	3115 ab	3496	2824	5376 b
Cowpea	-	3169 ab	3276	3060	4846 b
Sorghum	-	2695 b	3530	2681	7481 a
Sesame	-	3578 a	3418	2393	4959 b
Cover Crop	-	3513 a	3313	2820	4930 b
SEM	-	396	396	396	396

†Means within a column followed by different letters (a-c) within the same category are different statistically ($p < 0.05$).

§CT = conventional tillage; NT = no-till; and ST = strip till.

Table A.4. Wheat stand count, grain yield, and herbage mass by tillage treatment, and summer double crop treatment effects within year at Thrall location in Texas.

Thrall	Wheat stand count (plants m^{-2})				
Tillage	2016	2017	2018	2019	2020
CT§	78 b†	111 a	88	160	145 a
ST	91 a	64 b	86	131	94 b
NT	95 a	58 b	78	135	87 b
SEM	5	5	5	5	5
Double crop					
Fallow	92	68 b	89	152 a	107 c
Cowpea	86	81 ab	86	130 b	103 c
Sorghum	85	70 b	83	154 a	119 a
Sesame	88	81 ab	85	145 a	115 ab
Cover Crop	89	89 a	76	131 b	107 c
SEM	5	5	5	5	5
	Wheat grain yield (kg ha^{-1})				
	2016	2017	2018	2019	2020
CT	3433 b	2085 a	2931	1431 a	3613
ST	4030 a	1423 b	2707	1080 b	3280
NT	3931 a	1468 b	2903	969 b	3448
SEM	102	102	102	102	102
Fallow	3740	1478	3195 a	942 b	3080 c
Cowpea	3864	1693	3246 a	940 b	3596 ab
Sorghum	3789	1594	1787 c	1475 a	3559 ab
Sesame	3813	1808	3377 a	1499 a	3750 a
Cover Crop	3784	1720	2631 b	942 b	3251 b
SEM	120	120	120	120	120
	Wheat herbage mass (kg ha^{-1})				
	2016	2017	2018	2019	2020
CT	-	3449 a	8780	5674	8549
ST	-	3226 a	7748	5218	7131
NT	-	2382 b	8090	4697	7175
SEM		406	469	406	406
Fallow	-	2987 a	7249 a	4778 bc	7374
Cowpea	-	3032 a	8912 a	4534 bc	8380
Sorghum	-	2135 b	6101 b	5697 ab	7736
Sesame	-	3203 a	9410 a	6815 a	7587
Cover Crop	-	3571 a	7249 b	4158 c	7014
SEM	-	474	557	474	474

†Means within a column followed by different letters (a-c) within the same category are different statistically ($p < 0.05$).
§CT = conventional tillage; NT = no-till; and ST = strip till.

Table A.5. Summer double crop (cowpea, sesame, and sorghum) grain yields and herbage mass as impacted by tillage treatment at Beeville location in Texas.

Beeville	Cowpea grain yield (kg ha^{-1})					Cowpea herbage mass (kg ha^{-1})			
Tillage	2016	2017	2018	2019		2016	2017	2018	2019
CT§	99 ab†	399	-	624		1959 ab	2273	4168	1529
ST	146 a	592	-	509		857 b	2092	3566	1317
NT	42 b	266	-	393		3203 a	2769	3408	2068
SEM	25	191	-	123		588	276	423	534
	Sorghum grain yield (kg ha^{-1})					Sorghum herbage mass (kg ha^{-1})			
	2016	2017	2018	2019		2016	2017	2018	2019
CT	-	5281	1593	2168		-	11191	4565	6945 a
ST	-	3999	1244	2719		-	10124	6596	5636 b
NT	-	4519	2306	2310		-	9197	4984	8185 a
SEM	-	762	591	1064		-	821	1041	821
	Sesame seed yield (kg ha^{-1})					Sesame herbage mass (kg ha^{-1})			
	2016	2017	2018	2019		2016	2017	2018	2019
CT	749 a	359 a	590	1725		-	1332 a	2051 ab	968
ST	379 ab	503 a	542	1424		-	1574 a	1636 b	742
NT	217 b	122 b	589	1144		-	609 b	2718 a	797
SEM	111	62	66	380		-	177	345	221
						Cover crop herbage mass (kg ha^{-1})			
						2016	2017	2018	2019
CT	-	-	-	-		8775	5357	4551	2871
ST	-	-	-	-		7038	4981	4397	2073
NT	-	-	-	-		7896	4809	4173	1905
SEM	-	-	-	-		973	1103	782	486

†Tillage means within a column followed by different letters (a-b) within the same category and location are different statistically ($P < 0.05$).
§CT = conventional tillage; NT = no-till; and ST = strip till.

Table A.6. Summer double crop (cowpea, sesame, and sorghum) grain yields and herbage mass as impacted by tillage treatment at Lubbock location in Texas.

Lubbock	Cowpea grain yield (kg ha^{-1})					Cowpea herbage mass (kg ha^{-1})			
Tillage	2016	2017	2018	2019		2016	2017	2018	2019
CT§	824	1190	-	603		817	2259	1267	985
ST	739	1055	-	139		862	2038	1376	381
NT	649	934	-	355		917	2437	997	705
SEM	250	222	-	35		42	420	297	255
	Sorghum grain yield (kg ha^{-1})					Sorghum herbage mass (kg ha^{-1})			
	2016	2017	2018	2019		2016	2017	2018	2019
CT	3853	3148	3539	1028		4838	8169	7244	3086
ST	3044	3207	3129	469		5348	9767	7435	2143
NT	4719	4475	3478	1267		5733	11162	7937	2894
SEM	1031	588	602	212		325	1424	557	425
	Sesame seed yield (kg ha^{-1})					Sesame herbage mass (kg ha^{-1})			
	2016	2017	2018	2019		2016	2017	2018	2019

Table A.6. Continued

CT	1084 ab†	-	647	139		2163	-	1701	369
ST	725 b	-	691	227		1739	-	2547	479
NT	1099 a	-	491	296		2233	-	1716	371
SEM	117	-	117	104		262	-	231	155
						Cover crop herbage mass (kg ha^{-1})			
						2016	2017	2018	2019
CT	-	-	-	-		4160 a	5250	10977	2236
ST	-	-	-	-		1325 b	6806	9754	1865
NT	-	-	-	-		4576 a	5877	9624	1298
SEM	-	-	-	-		660	1123	1618	630

†Tillage means within a column followed by different letters (a-b) within the same category are different statistically (P < 0.05).
§CT = conventional tillage; NT = no-till; and ST = strip till.

Table A.7. Summer double crop (cowpea, sesame, and sorghum) grain yields and herbage mass as impacted by tillage treatment at Thrall location in Texas.

Thrall	Cowpea grain yield (kg ha^{-1})					Cowpea herbage mass (kg ha^{-1})			
Tillage	2016	2017	2018	2019		2016	2017	2018	2019
CT§	123	198 b†	-	357		297	847	1069	3046
ST	83	234 b	-	387		476	845	1165	3833
NT	76	517 a	-	463		365	835	1049	3564
SEM	35	59	-	62		90	140	357	460
	Sorghum grain yield (kg ha^{-1})					Sorghum herbage mass (kg ha^{-1})			
	2016	2017	2018	2019		2016	2017	2018	2019
CT	3923	3647	1538	3164 b		3153	6520	4205	5707 b
ST	4003	3449	2010	7803 a		4663	6363	4841	7293 ab
NT	4152	3727	1651	8102 a		4965	6668	4741	8211 a
SEM	548	258	251	1093		933	620	288	459
	Sesame seed yield (kg ha^{-1})					Sesame herbage mass (kg ha^{-1})			
	2016	2017	2018	2019		2016	2017	2018	2019
CT	436	706	702	920 b		750	2502 b	1879	1306 b
ST	1150	1141	731	1502 ab		1601	5229 a	2214	1508 ab
NT	1062	1519	842	1157 a		1534	6045 a	2105	1857 a
SEM	228	250	167	168		343	458	331	120
						Cover crop herbage mass (kg ha^{-1})			
						2016	2017	2018	2019
CT	-	-	-	-		1295	3908	1041 b	703
ST	-	-	-	-		1900	5910	1554 b	707
NT	-	-	-	-		2444	4816	2637 a	625
SEM	-	-	-	-		422	1472	615	198

†Tillage means within a column followed by different letters (a-b) within the same category are different statistically (P < 0.05).
§CT = conventional tillage; NT = no-till; and ST = strip till.

Table A.8. Single ring infiltration rate as impacted by year x tillage x summer double cropping interactions at Beeville and Lubbock, and year x tillage, year x summer double cropping at Thrall in Texas.

		Beeville infiltration rate (cm h^{-1})		
Tillage	Double crop	2017	2018	2020
CT§	Cover crop	-	23.8 a	13.2 abc
	Cowpea	-	8.5 d	15.7 ab
	Fallow	-	17.1 abc	10.4 bc
	Sesame		22.0 a	18.9 a
	Sorghum	-	9.8 d	12.8 abc
NT	Cover crop	-	10.7 cd	14.9 ab
	Cowpea	-	20.3 ab	6.6 c
	Fallow	-	12.5 cd	9.8 bc
	Sesame	-	13.9 bcd	18.6 a
	Sorghum	-	11.4 cd	19.5 a
SEM			2.8	2.8
		Lubbock infiltration rate (cm h^{-1})		
		2017	2018	2020
CT	Cover crop	12.4	12.6 b	18.7 a
	Cowpea	10.4	18.8 a	11.5 de
	Fallow	10.8	11.1 b	17.4 ab
	Sesame	9.2	13.2 b	14.3 bcd
	Sorghum	8.0	15.8 ab	16.4 abc
NT	Cover crop	6.6	8.7 b	16.1 abcd
	Cowpea	9.3	11.1 b	11.7 cde
	Fallow	8.0	17.7 a	8.7 e
	Sesame	9.0	13.4 ab	11.9 cde
	Sorghum	7.2	12.5 ab	12.6 cde
SEM		9.1	3.0	3.0
		Thrall infiltration rate (cm h^{-1})		
		2017	2018	2020
CT		6.2 a	9.9	19.2
NT		1.6 b	5.4	8.6
SEM		2.3	2.3	2.4
	Cover crop	2.6	4.3	8.0
	Cowpea	2.7	9.2	11.5
	Fallow	5.9	12.9	20.5
	Sesame	5.1	5.6	11.0
	Sorghum	3.3	6.1	18.4
SEM		3.2	3.1	3.3

†Means within a column followed by different letters (a-e) within the same category are different statistically ($P < 0.05$).

§CT = conventional tillage; NT = no-till; and ST = strip till.

Table A.9. Cornell steady state infiltration rate as affected by year x tillage, year x summer double cropping interactions at Beeville and Thrall, and year x tillage x summer double cropping at Lubbock in Texas.

		Beeville steady state infiltration rate (cm h^{-1})			
Tillage	Double crop	2017	2018	2019	2020
CT§		-	15.2	4.6	11.0
NT		-	12.3	5.7	11.0
SEM			1.1	0.9	1.0
	Cover crop	-	15.6	6.1	12.8
	Fallow	-	13.5	4.5	10.3
	Sorghum	-	12.2	4.9	10.0
SEM		-	1.2	0.9	1.1
		Lubbock steady state infiltration rate (cm h^{-1})			
		2017	2018	2019	2020
CT	Cover crop	8.5 ab	10.2	15.6 a	11.9
	Fallow	8.1 ab	12.5	9.0 b	11.9
	Sorghum	10.2 a	16.1	12.7 ab	13.9
NT	Cover crop	11.3 a	12.1	13.5 ab	11.9
	Fallow	10.5 a	12.9	16.4 a	8.4
	Sorghum	6.1 b	15.7	13.1 ab	13.8
SEM		1.6	1.7	1.8	2.0
		Thrall steady state infiltration rate (cm h^{-1})			
		2017	2018	2019	2020
CT		6.6	7.4	4.4	8.5
NT		5.6	6.3	5.2	7.3
SEM		0.8	0.8	0.8	0.9
	Cover crop	7.3	7.2	4.3	5.4 b
	Fallow	5.5	7.5	4.8	8.1 a
	Sorghum	5.6	6.0	5.3	10.2 a
SEM		0.8	1.0	0.9	1.0

†Means within a column followed by different letters (a-b) within the same category are different statistically ($P < 0.05$).
§CT = conventional tillage; NT = no-till; and ST = strip till.

Table A.10. Time-to-runoff as affected by tillage treatment, summer double crop treatment, and year effects for three locations in Texas.

	Beeville time-to-runoff (minutes)			
Tillage	2017	2018	2019	2020
CT§	-	8.1	4.6	3.9
NT	-	6.7	4.6	3.9
SEM		1.0	0.8	1.0
Double crop				
Cover crop	-	7.6	4.1	7.9 b
Fallow	-	6.9	4.1	8.3 b
Sorghum	-	7.7	5.5	10.1 a
SEM	-	1.2	1.0	1.1
	Lubbock time-to-runoff (minutes)			
	2017	2018	2019	2020
CT	3.9	7.3	3.5	3.7
NT	3.9	5.6	3.7	5.0
SEM	0.6	0.6	0.6	0.8
Cover crop	3.9	4.9	4.0	2.5 b
Fallow	4.1	7.8	3.8	3.9 b
Sorghum	3.8	6.7	3.0	6.7 a
Average	0.7	0.8	0.8	1.0
	Thrall time-to-runoff (minutes)			
	2017	2018	2019	2020
CT	3.0 a	7.8	4.4	5.1
NT	2.0 b	5.7	4.3	3.9
SEM	0.8	0.9	0.7	0.8
Cover crop	2.7	7.4	5.5	4.0
Fallow	2.1	7.6	3.8	5.6
Sorghum	2.7	5.2	3.7	3.8
SEM	0.9	1.0	0.8	1.0

†Means within a column followed by different letters (a-b) within the same category are different statistically ($P < 0.05$).

§CT = conventional tillage; NT = no-till; and ST = strip till.

Table A.11. Sorptivity as affected by tillage treatment, summer double crop treatment, and year effects for three locations in Texas.

	Beeville sorptivity (cm/min$^{1/2}$)			
Tillage	2017	2018	2019	2020
CT§	-	2.0	1.1	1.4
NT	-	1.7	1.4	1.7
SEM		0.2	0.2	0.2
Double crop				
Cover crop	-	1.8	1.2	1.5 b
Fallow	-	1.8	1.2	1.8 a
Sorghum	-	2.0	1.3	1.4 b
SEM	-	0.2	0.2	0.2
	Lubbock sorptivity (cm/min$^{1/2}$)			
	2017	2018	2019	2020
CT	1.4	1.7	1.5	1.0
NT	1.4	1.4	1.5	1.2
SEM	0.2	0.2	0.2	0.2
Cover crop	1.4	1.6	1.6	0.8 b
Fallow	1.3	1.4	1.5	1.2 a
Sorghum	1.5	1.6	1.3	1.4 a
SEM	0.2	0.2	0.2	0.2
	Thrall sorptivity (cm/min$^{1/2}$)			
	2017	2018	2019	2020
CT	1.3 a	1.89	1.1	1.7
NT	1.0 b	1.39	1.3	1.4
SEM	0.1	0.1	0.1	0.1
Cover crop	1.3 a	1.7	1.2	1.5
Fallow	1.0 b	1.7	1.2	1.5
Sorghum	1.2 ab	1.6	1.2	1.7
SEM	0.1	0.1	0.1	0.1

†Means within a column followed by different letters (a-b) within the same category are different statistically ($P < 0.05$).

§CT = conventional tillage; NT = no-till; and ST = strip till.

Table A.12. Runoff rate as affected by year x tillage, year x summer double cropping interactions at Beeville and Thrall, and year x tillage x summer double cropping at Lubbock in Texas.

		Beeville runoff rate (cm h^{-1})			
Tillage	Double crop	2017	2018	2019	2020
CT§		-	12.09	14.17	5.94
NT		-	15.40	14.12	11.58
SEM			2.1	1.7	2.0
	Cover crop	-	12.59	13.73	7.85
	Fallow	-	15.45	14.37	8.32
	Sorghum	-	13.20	14.34	10.10
SEM		-	2.4	1.9	2.3
		Lubbock runoff rate (cm h^{-1})			
		2017	2018	2019	2020
CT	Cover crop	15.7	20.5	19.4 ab	10.5
	Fallow	15.1	14.5	25.3 a	6.0
	Sorghum	15.6	17.2	22.8 a	7.8
NT	Cover crop	13.5	19.7	8.6 cd	10.9
	Fallow	13.2	12.6	3.4 d	16.6
	Sorghum	19.9	13.7	12.0 b	6.7
SEM		2.4	2.6	2.9	4.0
		Thrall runoff rate (cm h^{-1})			
		2017	2018	2019	2020
CT		18.1	16.2	20.9	16.2
NT		20.5	14.9	20.5	15.6
SEM		2.0	2.1	1.7	2.2
	Cover crop	17.9	14.2	18.6	14.5
	Fallow	20.0	14.1	22.4	15.4
	Sorghum	20.0	18.4	21.1	17.7
SEM		2.4	2.6	2.0	2.7

†Means within a column followed by different letters (a-d) within the same category are different statistically ($P < 0.05$).

§CT = conventional tillage; NT = no-till; and ST = strip till.

Table A.13. Wet aggregate stability as affected by tillage treatment, summer double crop treatment, and year effects for three locations in Texas.

	Beeville wet aggregate stability (%)		
Tillage	2017	2018	2019
CT§	-	15.0	16.9
ST		16.5 B	22.1 A
SEM		1.8	1.8
NT	-	17.1	18.8
Double crop			
Cover crop		15.6 A	21.0 B
Cowpea		17.2	17.5
Fallow	-	15.3 A	20.7 B
Sesame	-	15.6	18.1
Sorghum	-	17.4	19.1
SEM	-	1.7	1.7
	Lubbock wet aggregate stability (%)		
	2017	2018	2019
CT	8.1 B	18.6 A	19.6 A
ST	10.7 B	16.0 A	16.9 A
NT	11.3 B	16.2 A	20.1 A
SEM	1.5	1.6	1.6
Cover crop	10.8 B	15.6 A	15.8 A
Cowpea	10.0 B	18.1 A	21.6 A
Fallow	8.8 B	16.0 A	18.7 A
Sesame	10.7 B	18.6 A	18.7 A
Sorghum	9.9 B	16.3 A	19.6 A
SEM	2.0	2.0	2.0
	Thrall wet aggregate stability (%)		
	2017	2018	2019
CT	41.7 B	54.8 A	52.8 A
ST	30.8 B	49.0 AB	49.7 A
NT	33.2 B	53.2 A	50.4 A
SEM	2.8	2.8	2.8
Cover crop	35.9 B	52.2 A	50.9 A
Cowpea	34.6 C	49.9 B	57.3 A
Fallow	34.6 C	52.7 A	44.7 B
Sesame	35.2 B	52.1 A	53.5 A
Sorghum	35.8 B	54.7 A	48.3 A
SEM	3.4	3.4	3.4

†Means within a row followed by different uppercase letters (A-C) within the same category are different statistically ($P < 0.05$).

§CT = conventional tillage; NT = no-till; and ST = strip till.